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RESTRAINING ROLE OF LIGAND OXIDES AND RELATIVE REACTIVITY OF OXOVANADIUM(IV)-SALOPHEN COMPLEXES IN THE CATALYTIC OXIDATION OF PHENYLSULFINYLACETIC ACIDS BY HYDROGEN PEROXIDE

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ABSTRACT

A systematic study on the oxidative decarboxylation of a series of phenylsulfinylacetic acids (PSAAs) by hydrogen peroxide with three oxovanadium(IV)-salophen catalysts in the presence of ligand oxides in 100% acetonitrile medium is presented. The hydroperoxovanadium(V)-salophen generated from the reaction mixture is identified as the bonafide active oxidizing species. Introduction of electron donating groups (EDG) in the oxovanadium(IV)-salophen catalyst and electron withdrawing groups (EWG) in PSAA enhances the reactivity, whereas EWG in the catalyst and EDG in PSAA have a retarding effect on the reaction in the presence of ligand oxides. A Hammett correlation displays a non-linear downward curvature, which consists of two intersecting straight lines The importance of the ground state stabilization of PSAA is inferred from a linear Yukawa–Tsuno plot. Based on the observed substituent effects, a mechanism involving electrophilic attack of PSAA on the nucleophilic peroxo oxygen atom of the vanadium complex in the rate determining step followed by oxygen atom transfer is proposed.

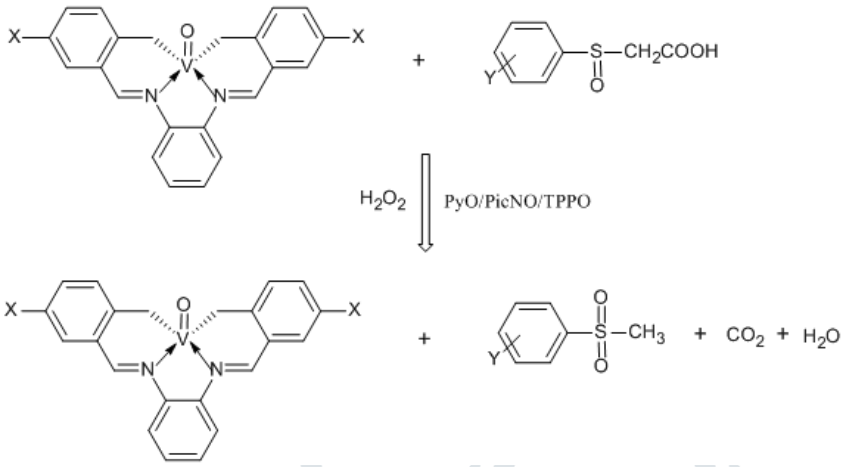
Keywords: oxovanadium(IV)-salophen, phenylsulfinylacetic acid, non-linear Hammett, oxidative decarboxylation, nitrogen base
***Abbreviations*:** PSAA, phenylsulfinylacetic acid; EWG, electron withdrawing group; EDG, electron donating group; Py, pyridine; ImH, imidazole; MeIm, 1-methylimidazole.

1.INTRODUCTION

The sulfoxide functional group is present in a number of biologically active molecules and is often involved in the metabolism of sulfides. Some of the phenyl sulfinyl compounds are found to possess high therapeutic effects. Vanadium mediated oxygen transfer reactions are frequently applied in chemical research and important advances have been achieved in catalytic and medicinal field. The heterocyclic *N*-oxide motif has proven to be a very productive emerging scaffold in drug discovery (Mfuh & Larionov, 2015). Heterocyclic N-oxides are also useful as protecting groups, auxiliary agents, oxidants, ligands in metal complexes and catalysts (Albini & Pietra, 1991). The application of N-oxide derivatives received considerable attention due to their usefulness as synthetic intermediates and biological importance. The pyridine *N*-oxide derivatives represent a unique class of antivirals. Several members have previously been found to be active against HIV-1 and/or HIV-2 and human cytomegalovirus (HCMV). Several of the pyridine *N*-oxide derivatives have been demonstrated to act at a post-integrational event in the replication cycle of HIV, i.e. HIV gene expression (Stevens et al. 2003). The oxide part on the pyridine moiety proved indispensable for anti-coronavirus activity

(Balzarini et al. 2006). Hence the study of role and action of N-oxides on the activity of metallo-enzymes is important in drug design.

Initially Srinivasan and co-workers (1986) have studied the influence of nitrogen and oxygen-donor ligands in metal-salen mediated epoxidation reaction. Subramaniam et al. (2016) have explained the effect of ligand oxides (LOs) in the oxidation kinetics of phenylsulfinylacetic acid (PSAA) and phenylmercaptoacetic acid by chromium salen complexes. The impeding effect of ligand oxides in the sulfoxidation of PMAA catalyzed by oxovanadium(IV)-salen complexes has also been studied (Kavitha et al. 2023). Hence kinetic studies were carried out on the redox reaction of PSAA with oxovanadium(IV)-salophen complexes and H_2O_2 in the presence of PyO, PicNO and TPPO. The overall reaction scheme is given below.



Complex: **I** : X = H; **II** : X = OCH_3; **III**: X = Cl
PSAA : Y = *p*-Cl, *m*-Cl, *p*-F, *p*-Br, H, *p*-Me, *p*-OEt, *p*-OMe,
Scheme 1. Overall reaction scheme for the oxidation of PSAA in the presence of LOs.

2. EXPERIMENTAL

2.1 Materials and Methods

Salicylaldehyde, 1,2-benzenediamine,$VOSO_4.5H_2O$, methanol, ethanol, H_2O_2 and acetonitrile were analytical grade, the ligand oxides like pyridine N-oxide (PyO), picoline N-Oxide (PicNO) and triphenylphosphine oxide (TPPO) were purchased from Sigma-Aldrich and were used as received.

A double beam BL 222 Elico UV–vis bio spectrophotometer with an inbuilt thermostat was employed to record the absorption spectra of oxovanadium(IV)-salophen complex. LC-MS was performed on a HPLC coupled Agilent ion trap mass spectrometer. Mass spectrometry was done using APCI (+) ionization technique. GC-MS data were acquired using Thermo GC-Trace ultra Ver: 5.0, Thermo MS DSQ II mass spectrometer. Infrared spectrum of the product was recorded using KBr pellet on a JASCO FT/IR-410 spectrophotometer.

2.2. Preparation of Phenylsulfinylacetic acids and Synthesis of oxovanadium(IV)-salophen complexes

The preparation of Phenylsulfinylacetic acid and its meta- and para-substituted acids and the synthesis of the oxovanadium(IV)-salophen complexes were accomplished by following the literature procedure as mentioned earlier (Jeevi Esther Rathnakumari et al. 2016).

2.3 Kinetic study

The kinetic study for the oxidation of PSAA and substituted PSAAs with H_2O_2 and oxovanadium(IV)-salophen complexes (**I-III**) in the presence of ligand oxides (LOs) pyridine N-oxide (PyO), picoline N-oxide (PicNO) and triphenylphosphine oxide (TPPO) were carried out in 100% acetonitrile medium under pseudo first-order conditions. The progress of the reaction was followed spectrophotometrically by monitoring the decrease in absorbance of the salophen complex at an appropriate wavelength of 396nm using a double beam BL 222 Elico UV-Vis spectrophotometer. The kinetics of the reaction was studied for different variations of the reactants, oxovanadium(IV)-salophen complex, PSAA and H_2O_2 at various initial concentrations keeping the other reaction conditions as constant. The pseudo first order rate constants were calculated from the slope of linear plots of log OD versus time. The second order rate constants were calculated by dividing the pseudo first order rate constants with the concentration of PSAA. The error in the rate constants was calculated according to 95% of the student's t-test.

2.4 Product analysis

The experimental procedure for the analysis and characterization of the product was in accordance with our previous publication on the oxidative decarboxylation of PSAA in the absence of ligand oxides (Jeevi Esther Rathnakumari et al. 2016). Formation of methyl phenyl sulfone was identified as the only product of the reaction by FT-IR and GC-MS.

3. RESULTS

3.1 Absorption spectral studies

The absorbance of oxovanadium(IV)-salophen (**I**) at 396 nm do not shift by the addition of ligand oxides. Also there is no increase in the optical density. In the presence of ligand oxide also, it is noted that addition of H_2O_2 at higher concentration to the complex shows an increase in intensity of a new broad absorption peak at 610 nm after a time interval, followed by a decrease during the course of time which demonstrates the formation of hydroperoxovanadium(V) species in the reaction mixture.

The formation as well as the involvement of peroxovanadium(V) species as an active intermediate was also confirmed in the peroxidative oxidation of benzene and mesitylene by vanadium(IV) and (V) complexes with nitrogen and oxygen containing ligand catalyst (Jeevi Esther Rathnakumari et al. 2016), sulfides and benzoin by polystyrene bound oxidovanadium(IV) as well as dioxidovanadium(V)(Reis et al. 2004) and sulfides and styrene by oxovanadium(IV) complex catalyzed by nitrogen and sulfur containing donor ligands (Maurya et al. 2007 & 2009).

3.2 Effect of reactants on reaction rate

During the kinetic runs in the H_2O_2 oxidation of PSAA with oxovanadium(IV)-salophen complexes in the presence of LOs, again a well defined induction period for a certain period of time followed by a gradual decrease in absorbance is observed similar to the one noted in the absence (Jeevi Esther Rathnakumari, et al. 2016) and presence of nitrogen bases (Jeevi Esther Rathnakumari, et al. 2023). A plot of log(OD) *vs.* time for the complex **II** at different H_2O_2 concentrations in the presence of PyO are shown in Figure 1.

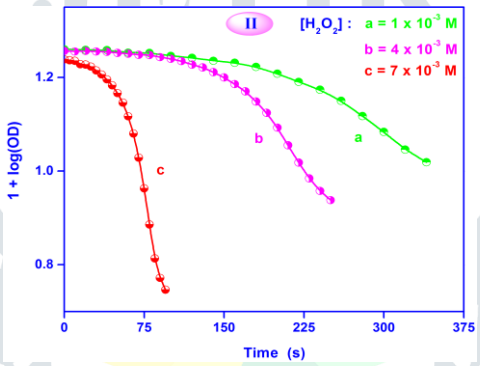


Figure 1 Pseudo first order plots at different $[H_2O_2]$.
$[PSAA] = 7.0 \times 10^{-2}$ M; [**II**] $= 5.0 \times 10^{-4}$ M; $[PyO] = 5.0 \times 10^{-4}$ M.

The induction period is found to decrease with the increase in the concentration of H_2O_2. The pseudo first-order rate constants calculated from the pseudo first-order plots at different concentration of H_2O_2 with three different complexes and LOs are given in Table 1. The effect of $[H_2O_2]$ on reaction rate in the presence of three LOs shows that the rate increases with increase in $[H_2O_2]$ and beyond the optimum range the reaction rate is found to decrease with hydrogen peroxide concentration.

Table 1 Effect of $[H_2O_2]$ in the presence of ligand oxides

10^3 $[H_2O_2]$ (M)	10^3 k_1 (s^{-1})		
	PyO	PicNO	TPPO
		I	
2.0	0.821 ± 0.03	0.523 ± 0.02	0.243 ± 0.02
4.0	1.473 ± 0.05	1.08 ± 0.04	0.610 ± 0.03
7.0	4.03 ± 0.11	3.53 ± 0.07	1.99 ± 0.06
9.0	6.92 ± 0.09	5.88 ± 0.15	2.31 ± 0.08
11.0	5.11 ± 0.06	4.35 ± 0.17	2.00 ± 0.04
		II	
2.0	11.3 ± 0.06	9.12 ± 0.05	4.01 ± 0.04
4.0	26.1 ± 0.88	21.6 ± 0.15	11.3 ± 0.06
7.0	40.5 ± 0.81	31.9 ± 0.32	23.1 ± 0.24
9.0	51.0 ± 0.33	40.2 ± 0.20	29.0 ± 0.13
11.0	48.2 ± 0.57	37.6 ± 0.63	22.3 ± 0.41
		III[a]	
2.0	0.061 ± 0.02	0.041 ± 0.02	0.019 ± 0.01

4.0	0.290 ± 0.04	0.195 ± 0.01	0.108 ± 0.02
7.0	0.881 ± 0.08	0.703 ± 0.03	0.585 ± 0.02
9.0	1.71 ± 0.10	1.42 ± 0.09	1.05 ± 0.05
11.0	1.54 ± 0.11	1.22 ± 0.06	0.837 ± 0.12

[PSAA] = 7.0×10^{-2} M; solvent = 100% CH_3CN; Temp. = 30 °C; **[I]** = **[II]** = 5.0×10^{-4} M; **[III]** = 1.0×10^{-4} M; [PyO] = [PicNO] = [TPPO] = 5.0×10^{-4} M.
[a][PyO] = [PicNO] = 5.0×10^{-4} M; [TPPO] = 5.0×10^{-5} M.

The effect of PSAA on the reaction rate in the presence of three ligand oxides namely PyO, PicNO, TPPO was studied by measuring the rate of the reaction at different [PSAA] The values of pseudo first-order and second- order rate constants calculated are given in Table 2. The pseudo first-order rate constants (k_1) increase with the increase in [PSAA] and the second order rate constant (k_2) calculated using the relation k_1/[PSAA] are found to be constant for all the three oxovanadium(IV)-salophen complexes. The pseudo first-order plot at different [PSAA] (Fig. 2), the linear plot between k_1 and [PSAA] passing through the origin (Fig. 3) and the unit slope values observed in the plots of log k_1 *vs.* log [PSAA] with different LOs (Fig. 4) for all the three oxovanadium(IV)-salophen complexes confirm the first order dependence on PSAA.

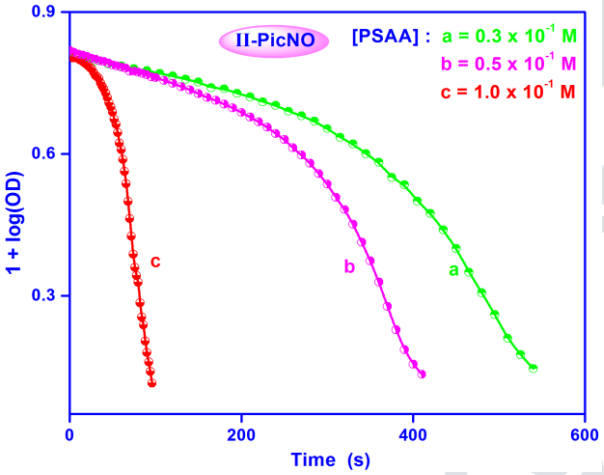


Figure 2 Pseudo first-order plots at different [PSAA]. $[H_2O_2] = 3.0 \times 10^{-3}$M; **[II]** = 5.0×10^{-4} M; [PicNO] = 5.0×10^{-4} M.

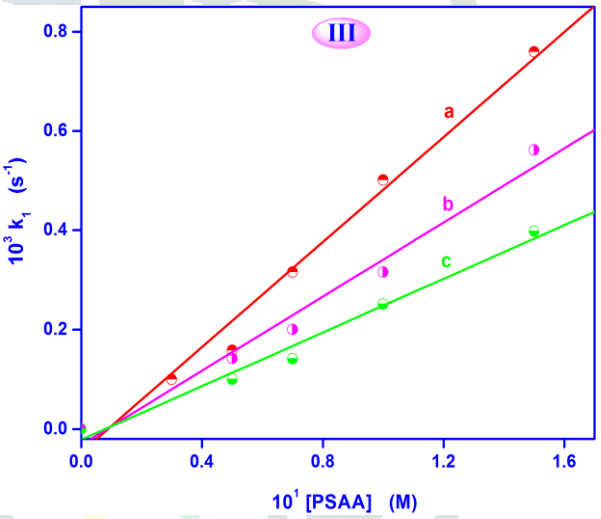


Figure 3 Plots of k_1 *vs.* [PSAA] for the reactions. a = PyO; b = PicNO; c = TPPO. General conditions as in Table 2.

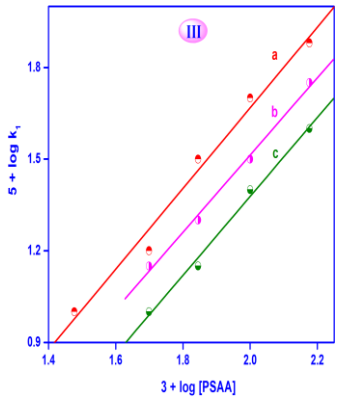


Figure 4 Double logarithmic plots of k_1 and [PSAA]. a = PyO; b = PicNO; c = TPPO. General conditions as in Table 2.

Table 2 Effect of [PSAA] in the presence of ligand oxides.

10^1 [PSAA] (M)	PyO		PicNO		TPPO	
	10^3k_1 (s^{-1})	10^2k_2 ($M^{-1}s^{-1}$)	10^3k_1 (s^{-1})	10^2k_2 ($M^{-1}s^{-1}$)	10^3k_1 (s^{-1})	10^2k_2 ($M^{-1}s^{-1}$)
0.30	0.490 ± 0.01	1.63 ± 2.3	0.338 ± 0.03	1.13 ± 1.0	0.210 ± 0.01	0.70 ± 0.33
0.50	0.891 ± 0.04	1.78 ± 0.8	0.678 ± 0.07	1.36 ± 1.4	0.401 ± 0.03	0.80 ± 0.60
0.70	1.63 ± 0.10	2.30 ± 1.4	1.15 ± 0.02	1.64 ± 0.29	0.702 ± 0.05	1.00 ± 0.71
1.00	2.18 ± 0.06	2.18 ± 0.60	1.63 ± 0.18	1.63 ± 1.1	1.06 ± 0.06	1.06 ± 0.60
1.50	3.10 ± 0.14	2.07 ± 0.93	2.25 ± 0.20	1.50 ± 1.3	1.08 ± 0.10	1.12 ± 0.67
0.30	13.2 ± 0.05	44.0 ± 1.67	12.6 ± 0.13	42.0 ± 4.30	6.03 ± 0.05	20.1 ± 1.67
0.50	21.4 ± 0.31	42.0 ± 6.2	17.8 ± 0.20	35.4 ± 4.0	9.83 ± 0.12	19.7 ± 2.4
0.70	28.0 ± 0.09	40.0 ± 1.3	24.0 ± 0.16	34.3 ± 2.3	12.5 ± 0.23	17.9 ± 3.3
1.00	37.9 ± 0.22	37.9 ± 2.2	31.6 ± 0.40	31.6 ± 4.0	17.8 ± 0.20	17.8 ± 2.0
1.50	48.8 ± 0.10	32.5 ± 0.67	44.7 ± 0.28	29.8 ± 1.9	23.9 ± 0.16	15.9 ± 1.1
0.30	0.100 ± 0.02	0.33 ± 0.67	-	-	-	-
0.50	0.158 ± 0.05	0.32 ± 1.0	0.142 ± 0.03	0.28 ± 0.60	0.100 ± 0.01	0.20 ± 0.20
0.70	0.316 ± 0.07	0.45 ± 1.0	0.200 ± 0.02	0.29 ± 0.29	0.141 ± 0.03	0.20 ± 0.43
1.00	0.501 ± 0.13	0.50 ± 1.3	0.316 ± 0.04	0.32 ± 0.40	0.251 ± 0.07	0.251 ± 0.70
1.50	0.759 ± 0.11	0.57 ± 0.73	0.562 ± 0.06	0.37 ± 0.40	0.398 ± 0.09	0.265 ± 0.60

[**I**] = 5.0 × [**III**] = 10^{-4} M; = [PicNO] = [TPPO] = 5.0 × 10^{-4} M; [**II**] = 10^{-4} M, 1.0 × [PyO]

[a][PyO] = [a][PicNO] = 5.0 × 10^{-4} M; [a][TPPO] = 5.0 × 10^{-5} M; Temp = 30 °C; solvent = 100 % CH_3CN; $[H_2O_2]$ = 3.0 × 10^{-3} M

The pseudo first-order rate constant increases with increase in concentration of oxovanadium(IV)-salophen complexes in the presence of LOs which is similar to that observed in the presence of nitrogen bases (Table 3).

Table 3 Effect of [complex] (**I–III**) in the presence of ligand oxides

10^4 [Complex] (M)	10^3 k_1 (s^{-1})		
	PyO	PicNO	TPPO
	I		
0.1	2.03 ± 0.02	1.74 ± 0.04	0.573 ± 0.02
0.50	2.58 ± 0.08	2.40 ± 0.09	0.920 ± 0.05
1.0	2.91 ± 0.03	2.89 ± 0.13	1.28 ± 0.01
2.5	3.57 ± 0.06	3.22 ± 0.20	1.68 ± 0.08
5.0	4.03 ± 0.11	3.53 ± 0.07	1.99 ± 0.06
	II		
0.1	20.8 ± 0.21	17.1 ± 0.10	10.1 ± 0.08
0.50	25.9 ± 0.65	20.3 ± 0.34	14.2 ± 0.40
1.0	31.2 ± 0.07	23.1 ± 0.5	17.0 ± 0.15
2.5	36.1 ± 0.30	28.40 ± 0.50	20.3 ± 0.6
5.0	40.5 ± 0.81	31.9 ± 0.32	23.1 ± 0.24
	III[a]		
0.1	0.231 ± 0.03	0.099 ± 0.01	0.053 ± 0.02
0.50	0.452 ± 0.02	0.285 ± 0.06	0.201 ± 0.04
1.0	0.881 ± 0.08	0.703 ± 0.03	0.585 ± 0.02
2.5	1.21 ± 0.10	1.01 ± 0.09	0.710 ± 0.03
5.0	1.55 ± 0.13	1.38 ± 0.10	0.931 ± 0.05

[PSAA] = 7.0 × 10^{-2} M; $[H_2O_2]$ = 7.0 × 10^{-3} M; Temp = 30 °C; Solvent = 100% CH_3CN
[PyO] = [PicNO] = [TPPO] = 5.0 × 10^{-4} M;
[a][PyO] = [PicNO] = 5.0 × 10^{-4} M; [TPPO] = 5.0 × 10^{-5} M

From Table 3 it is inferred that the substituents in the salophen ligand of the complex influence the rate of the reaction to a greater extent. Electron releasing methoxy substituent in the 5,5′-positions of oxovanadium(IV)-salophen complex increases the reaction rate while electron withdrawing chloro substituent in 5,5′-positions decreases the rate of the reaction. Thus the observed order of reactivity among the oxovanadium(IV)-salophen complexes in the presence of ligand oxides is 5,5′-$(OCH_3)_2$ oxovanadium(IV)-salophen > unsubstituted > 5,5′-Cl_2 oxovanadium(IV)-salophen.

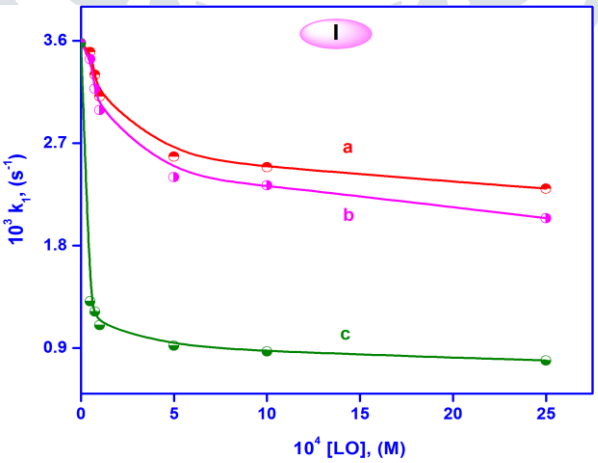
3.3 Effect of ligand oxides on reaction rate

Table 4 Influence of ligand oxides on the reactions of PSAA with H_2O_2 catalysed by **I**, **II** and **III**.

10^3 [LO] (M)	10^3 k_1 (s^{-1})		
	PyO	PicNO	TPPO
	I		
0	3.58 ± 0.11	3.58 ± 0.11	3.58 ± 0.11
0.050	3.50 ± 0.23	3.44 ± 0.30	1.31 ± 0.09
0.075	3.30 ± 0.14	3.18 ± 0.15	1.22 ± 0.07
0.10	3.11 ± 0.09	2.99 ± 0.20	1.10 ± 0.01
0.50	2.58 ± 0.08	2.40 ± 0.09	0.92 ± 0.05
1.0	2.49 ± 0.05	2.33 ± 0.04	0.87 ± 0.02
2.5	2.30 ± 0.07	2.04 ± 0.03	0.79 ± 0.06
	II		
0	45.4 ± 0.19	45.4 ± 0.19	45.4 ± 0.19
0.050	43.7 ± 0.20	42.5 ± 0.23	26.9 ± 0.26
0.075	36.3 ± 0.18	37.7 ± 0.30	22.9 ± 0.17
0.10	30.8 ± 0.43	31.6 ± 0.09	20.8 ± 0.24
0.50	25.9 ± 0.65	20.3 ± 0.34	14.2 ± 0.40
1.0	23.0 ± 0.30	18.5 ± 0.14	12.9 ± 0.09
2.5	17.8 ± 0.07	17.1 ± 0.05	11.2 ± 0.20
	III		
0	0.646 ± 0.05	0.646 ± 0.05	0.646 ± 0.05
0.050	0.639 ± 0.06	0.595 ± 0.04	0.201 ± 0.04
0.075	0.574 ± 0.08	0.491 ± 0.03	0.143 ± 0.07
0.10	0.526 ± 0.07	0.402 ± 0.02	0.111 ± 0.03
0.50	0.452 ± 0.02	0.285 ± 0.06	0.072 ± 0.01
1.0	0.434 ± 0.03	0.257 ± 0.03	0.066 ± 0.02
2.5	0.415 ± 0.04	0.143 ± 0.01	0.050 ± 0.01

[PSAA] = 7.0×10^{-2} M; [H_2O_2] = 7.0×10^{-3} M; [**I**] = [**II**] = [**III**] = 5.0×10^{-5} M; Temp = 30 °C; solvent = 100 % CH_3CN.

The pseudo first-order rate constant values calculated in the absence of ligand oxides and at various ligand oxide concentrations for the different oxovanadium(IV)-salophen complexes are presented in Table 4. The reactions could not be carried out at higher concentrations of LOs as the rate of the reactions was too slow to be measured.



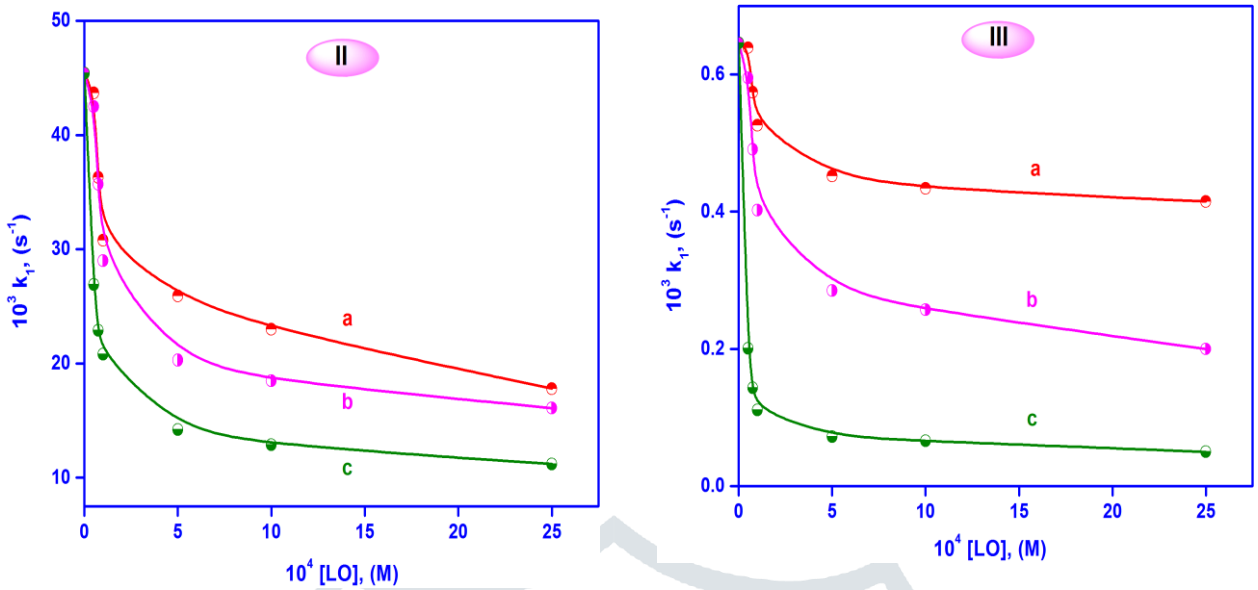


Figure 5 Plots of k_1 *vs.* [LO]
a = PyO; b = PicNO; c = TPPO. General conditions as in Table 4.

The data in Table 4 and Figure 5 clearly show that the extent of rate retardation observed at low concentrations of LO is comparatively more than at higher concentrations. The reaction shows most retardation and least reactivity with TPPO among the three different LOs and PyO shows least retardation effect and highest reactivity. Thus, the retardation effect shown by the LOs in all the three oxovanadium(IV)-salophen complexes is found to be TPPO > PicNO > PyO.

3.4. Effect of Substituents and Linear free energy relationship

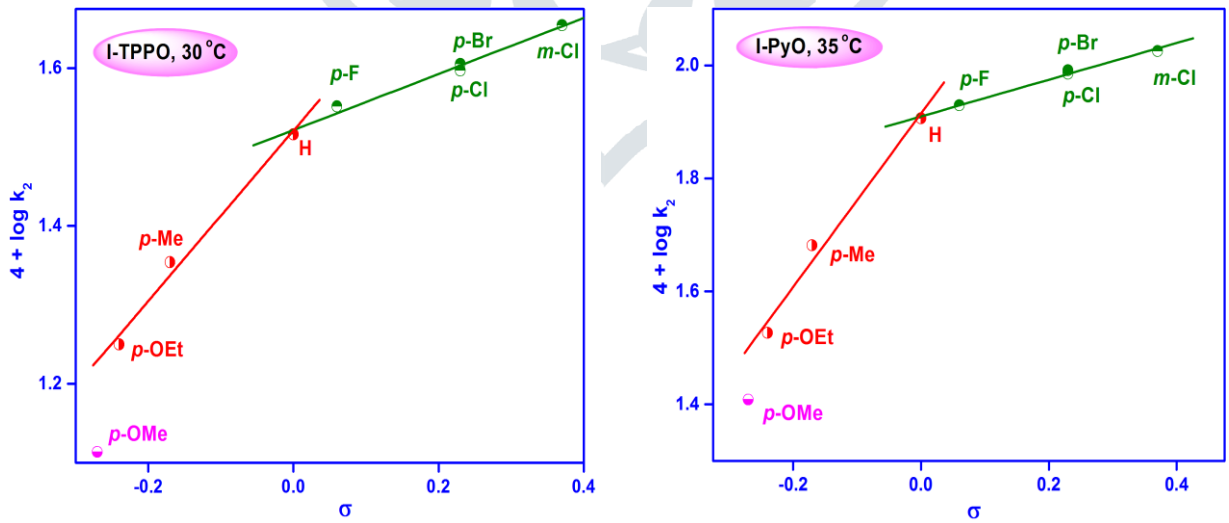
The kinetic data in the Table 5 indicate that the reactions in the presence of LOs are sensitive to the nature of the substituents in the aryl moiety of PSAA and in the phenolic part of the salophen ligand. Electron withdrawing groups (EWG) in the phenyl ring of PSAA and electron donating groups (EDG) in the salophen ligand of the complex enhance the rate, while EDG in the phenyl ring of PSAA and EWG in the salophen ligand decrease the reaction rate. In order to confirm the extent of charge separation in the transition state of the reaction, the rate constant values are analysed in terms of Hammett σ values. Since EDG in PSAA retard the reaction rate and EWG in the same accelerate the reaction, a non-linear Hammett plot with downward curvature is seen with all LOs. The Hammett plots are found to have small positive ρ value for EWG (ρ^+ = 0.277 to 0.459) and a fairly high positive ρ value for EDG (ρ^+ = 1.03 to 1.54). The positive ρ values obtained in the present reaction series point out that PSAA acts as an electrophile in the reaction. The representative Hammett plots are shown in Figure 6.

Table 5 Second order rate constants and thermodynamic parameters for the reactions of PSAAs by H_2O_2 in the presence of ligand oxides and complex **I**.

Y	10^2 k_2 (M^{-1} s^{-1})			$\Delta^{\ddagger}H$ ($kJmol^{-1}$)	$\Delta^{\ddagger}S$ ($JK^{-1}mol^{-1}$)
	25 °C	30 °C	35 °C		
			PyO		
p-Cl	5.60 ± 0.03	7.88 ± 0.32	9.80 ± 0.15	42.8 ± 2.2	125 ± 6.1
m-Cl	6.26 ± 0.12	8.88 ± 0.31	10.6 ± 0.32	40.4 ± 1.8	132 ± 5.4
p-F	5.16 ± 0.34	6.5 ± 0.08	8.50 ± 0.08	38.1 ± 2.0	142 ± 3.3
p-Br	5.50 ± 0.08	7.52 ± 0.15	9.66 ± 0.22	43.1 ± 1.6	125 ± 2.5
H	4.84 ± 0.05	5.96 ± 0.10	8.06 ± 0.10	38.8 ± 2.7	140 ± 9.4
p-Me	3.28 ± 0.03	3.98 ± 0.02	4.80 ± 0.06	29.3 ± 2.1	176 ± 7.2
p-OEt	2.72 ± 0.01	3.00 ± 0.03	3.36 ± 0.04	16.2 ± 1.0	221 ± 4.8
p-OMe	1.80 ± 0.02	2.22 ± 0.05	2.56 ± 0.01	26.9 ± 0.3	188 ± 8.9
ρ_{EWG}	0.277 ± 0.02	0.459 ± 0.01	0.326 ± 0.02		

r	0.982	0.993	0.996		
ρ_{EDG}	1.03 ± 0.04	1.20 ± 0.03	1.54 ± 0.04		
r	0.992	0.991	0.992		
			PicNO		
p-Cl	5.38 ± 0.02	7.02 ± 0.04	8.20 ± 0.10	32.2 ± 2.8	161 ± 9.3
m-Cl	5.96 ± 0.05	7.94 ± 0.21	8.86 ± 0.08	30.3 ± 1.9	166 ± 8.8
p-F	4.68 ± 0.08	6.02 ± 0.02	7.14 ± 0.23	32.2 ± 2.2	162 ± 7.4
p-Br	5.30 ± 0.20	7.04 ± 0.10	8.04 ± 0.31	31.9 ± 3.3	162 ± 6.4
H	4.40 ± 0.11	5.42 ± 0.15	6.76 ± 0.17	32.9 ± 4.1	161 ± 10.1
p-Me	2.90 ± 0.03	3.46 ± 0.08	3.76 ± 0.09	19.9 ± 3.2	208 ± 9.4
p-OEt	2.44 ± 0.04	2.80 ± 0.04	3.20 ± 0.06	20.7 ± 2.7	206 ± 3.8
p-OMe	1.66 ± 0.01	2.02 ± 0.06	2.38 ± 0.05	27.4 ± 1.5	187 ± 4.2
ρ_{EWG}	0.351 ± 0.02	0.435 ± 0.03	0.319 ± 0.03		
r	0.998	0.993	0.996		
ρ_{EDG}	1.07 ± 0.05	1.19 ± 0.04	1.38 ± 0.02		
r	0.999	0.999	0.997		
			TPPO		
p-Cl	3.50 ± 0.06	4.02 ± 0.05	5.50 ± 0.22	34.3 ±2.1	158 ± 4.5
m-Cl	3.96 ± 0.10	4.50 ± 0.09	6.02 ± 0.31	31.9 ± 3.3	165 ± 3.9
p-F	3.16 ± 0.08	3.56 ± 0.11	4.68 ± 0.16	29.9 ± 2.5	174 ± 8.1
p-Br	3.60 ± 0.13	3.96 ± 0.14	5.40 ± 0.09	30.8 ± 4.2	170 ± 10.5
H	2.92 ± 0.09	3.28 ± 0.14	4.36 ± 0.12	30.5 ± 1.5	173 ± 6.3
p-Me	2.02 ± 0.07	2.26 ± 0.04	2.82 ± 0.07	25.4 ± 1.3	192 ± 7.8
p-OEt	1.58 ± 0.08	1.78 ± 0.07	2.08 ± 0.05	20.7 ± 2.0	210 ± 2.6
p-OMe	1.02 ± 0.05	1.30 ± 0.03	1.58 ± 0.02	33.4 ± 2.8	171 ± 9.4
ρ_{EWG}	0.344 ± 0.04	0.355 ± 0.02	0.379 ± 0.01		
r	0.991	0.993	0.995		
ρ_{EDG}	1.08 ± 0.06	1.08 ± 0.05	1.29 ± 0.05		
r	0.995	0.994	0.992		

[PSAA] = 5.0×10^{-2} M; [H_2O_2] = 7.0×10^{-3} M; [**I**] = 3.0×10^{-4} M; [PyO] = [PicNO] = [TPPO] = 5.0×10^{-4} M; solvent = 100 % CH_3CN.



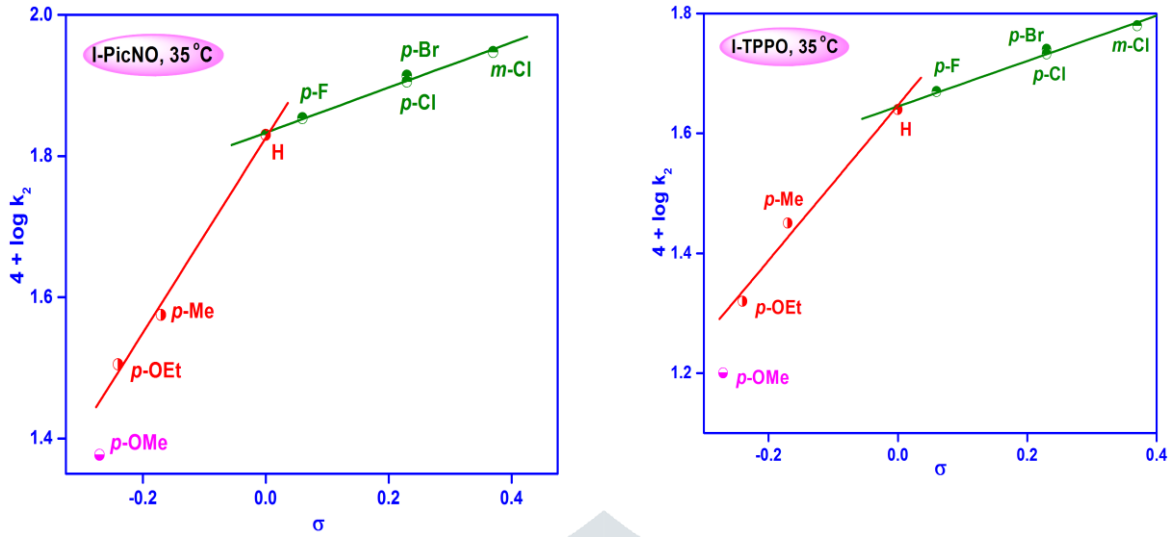


Figure 6 Hammett plots for the substituent variation in PSAA in the presence of ligand oxides: General conditions as in Table 5

3.5 Influence of temperature and thermodynamic parameters

The kinetics of the reaction is followed at three different temperatures 25 ºC, 30 ºC, 35 ºC for all PSAAs with complex **I** and at 30 ºC, 35 ºC, 40 ºC for PSAA with complexes **II** and **III** in the presence of LOs. The second order rate constants and the thermodynamic parameters are calculated using Eyring's plot of $\log(k_2/T)$ against 1/T (Fig. 7). The positive $\Delta^{\ddagger}H$ values in Table 5 and 6 show the endothermic nature of the reaction and the high negative $\Delta^{\ddagger}S$ values indicate the involvement of structured transition state in the mechanism.

Table 6 Second order rate constants at different temperatures and thermodynamic parameters.

Ligand oxide	10^2k_2 (M^{-1} s^{-1})			$\Delta^{\ddagger}H$ (kJ mol^{-1})	$-\Delta^{\ddagger}S$ (JK^{-1} mol^{-1})
	30 ºC	35 ºC	40 ºC		
			II		
PyO	37.0±0.65	44.4±2.4	54.3±1.9	27.9±1.3	161.5±7.2
PicNO	29.0±0.34	34.4± 1.7	38.9±1.1	20.6±0.91	187.4±5.8
TPPO	20.3±0.40	25.3± 0.60	28.7±0.71	25.0±1.0	176.8±9.3
			III[a]		
PyO	0.646±0.02	1.69±0.08	2.84±0.10	114.9±3.4	91.6±1.4
PicNO	0.407± 0.06	0.970±0.05	1.76±0.04	113.5±6.1	83.8±2.3
TPPO	0.287±0.04	0.749±0.02	1.26±0.06	114.3±5.2	83.9±2.7

[PSAA] = 7.0×10^{-2} M; [H_2O_2] = 7.0×10^{-3} M; [**I**] = [**II**] = [**III**] = 5.0×10^{-5} M; [PyO] = [PicNO] = [TPPO] = 5.0×10^{-4} M; [a][PyO] = [a][PicNO] = 5.0×10^{-4} M; [a][TPPO] = 5.0×10^{-5} M; solvent = 100 % CH_3CN.

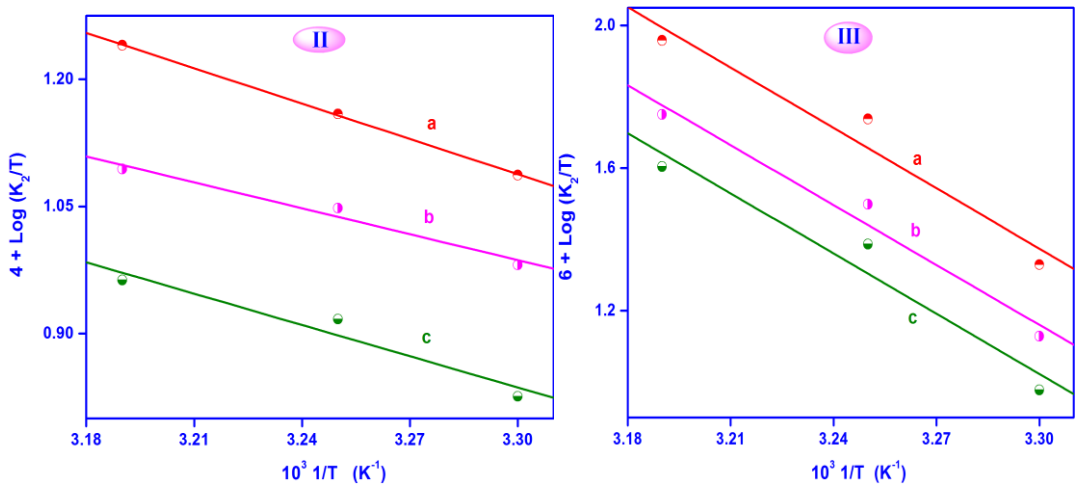


Figure 7 Eyring plots for the reaction in the presence of ligand oxides.
a = PyO; b = PicNO; c = TPPO.

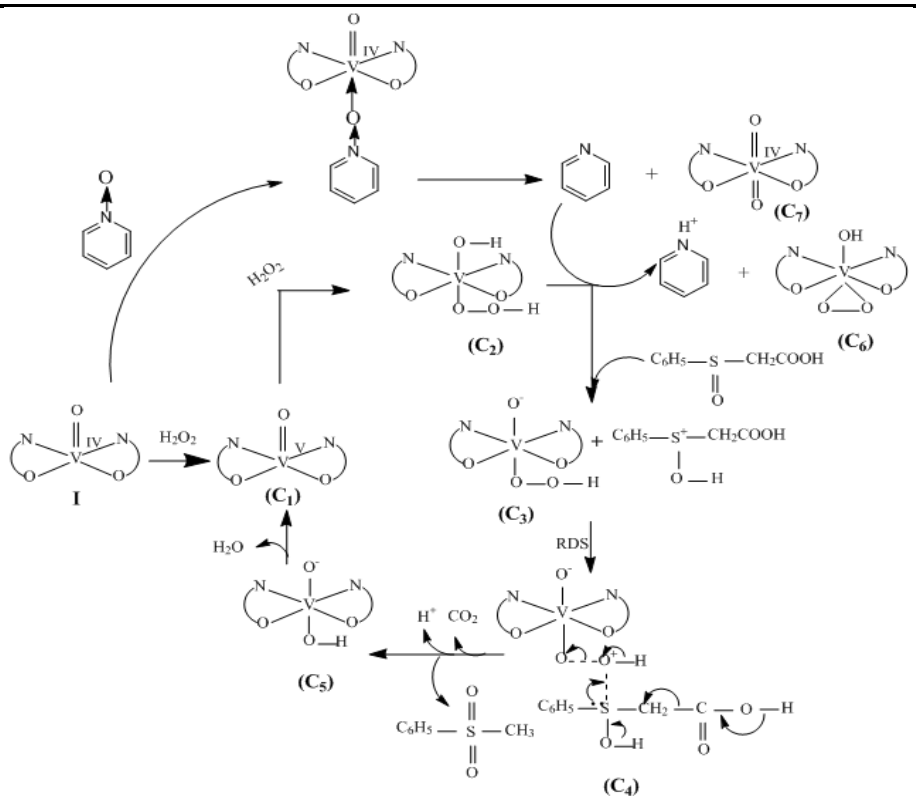
4.DISCUSSION

4.1 Mechanism

Oxovanadium(IV)-salophen complex is first oxidized to oxovanadium(V) salophen (**C_1**) by H_2O_2 which further reacts with excess of hydrogen peroxide to form the active species, hydroperoxovanadium(V) salophen (**C_2**). The PSAA then abstracts a proton from the acidic hydroxyl group of the active species (**C_2**) and thus (**C_2**) is transformed into intermediate (**C_3**). This proton transfer polarizes the sulfoxide group of PSAA, rendering it electrophilic in nature. The electrophilic nature of PSAA in the present study is confirmed from positive ρ values obtained from the Hammett correlation for both electron donating and electron withdrawing groups of PSAA and the observed substituent effect in the presence of LOs. Based on these observations, an electrophilic attack of sulfur atom of PSAA on the peroxo nucleophilic oxygen leading to the formation of the transition state (**C_4**) in a slow rate determining step is proposed for this reaction. All these changes are schematically represented in Scheme 2. The RDS proposed in the reaction is found to be in consistence with the observed substitiuent effects. The rate is found to increase with EDG in the complex and EWG in PSAA and decrease in the case of EWG in the complex and EDG in PSAA. Finally, a fast internal oxygen atom transfer takes place in the intermediate (**C_4**) leading to the formation of methyl phenyl sulfone with the regeneration of oxovanadium(V) complex.

In the presence of LO, with the increase in concentration of oxovanadium(IV)-salophen complexes the rate of the reaction is found to increase. This may be attributed to the involvement of the complex in the formation of adduct rather than indulging in the decomposition of H_2O_2 which can thus lead to an increase in the rate of reaction. The reaction rate decreases at high concentrations of hydrogenperoxide in all the three complexes (**I-III**) which is due to the conversion of vanadium complex into inorganic peroxovanadate.

In the present study, linear Yukawa-Tsuno plots observed not only confirm a common mechanism for all PSAAs but also prove that the ground state stabilization of PSAAs through resonance interaction is the cause for the observed non linearity in the Hammett plots as reported in the earlier paper. (Jeevi Esther Rathnakumari, et al. 2024).



Scheme 2. Mechanistic pathway for the oxidative decarboxylation of PSAA by H_2O_2 in the presence of ligand oxides.

4.2 Restraining role of ligand oxides

From the kinetic data it is found that the added LOs show an impeding effect on the reaction rate which is a rare and unique observation and no such related kinetic study has been yet reported. On the addition of LO, the active oxidizing species concentration necessary for the oxidation of PSAA is found to decrease. This may be attributed by utilization of oxovanadium(IV)-salophen (**C_1**) for adduct formation with LO. The adduct being less stable, undergoes N-O cleavage resulting in the formation of free base and the dioxovanadium complex. In the kinetic and thermodynamic study of cleavage of the N-O bond of N-oxides by a vanadium complex, Palluccio et al. (2013) have shown that PyO forms a adduct with the vanadium complex followed by oxygen atom transfer in a separate step. Time resolved spectral changes at low temperature have shown the binding of ligand to the vanadium centre and the subsequent oxygen atom transfer. The adduct formed between the complex and PyO has been separated at low temperature and from kinetic studies, the process has been proved as an irreversible one. They also pointed out that adduct formation is too rapid at higher temperatures and instantaneously cleaves to form pyridine and oxo vanadium complex. The N-O bond cleavage in the adduct has also been proved by Laplaza et al. (1995). Thermo chemical study of oxygen atom transfer shows that the V-O bond formed in the complex due to N-O cleavage is stronger compared to the N-O bond cleaved. In the oxovanadium(IV)-salen catalysed oxidation of tertiary amines by H_2O_2, Madhavan et al. (2015) have proved that N-oxide formed as the product binds to the oxovanadium(IV) centre which accounts for the low yield of N-oxide formed in the reaction. The vanadium(IV)-N-oxide then undergoes N-O cleavage to form the free base. Brask et al. (2002) also have shown the formation of free pyridine, when PyO is added to the vanadium(III) trisanilide complex.

Thus on the basis of the above supporting evidences, it is proposed that in the present study, adduct is formed between the oxovanadium(IV)-salophen complex and LO in a parallel reaction with the formation of reactive species (**C_2**). This results in decrease in concentration of active species and accounts for the decrease in rate with increase in concentration of LO (Table 4). The adduct formed between **I** and PyO and PicNO then undergoes N-O cleavage resulting in the formation of a dioxovanadium complex (**C_7**) and the free bases pyridine and 4-methyl pyridine (Fig. 8). No such cleavage has been reported in the adduct formed between the complex and TPPO.

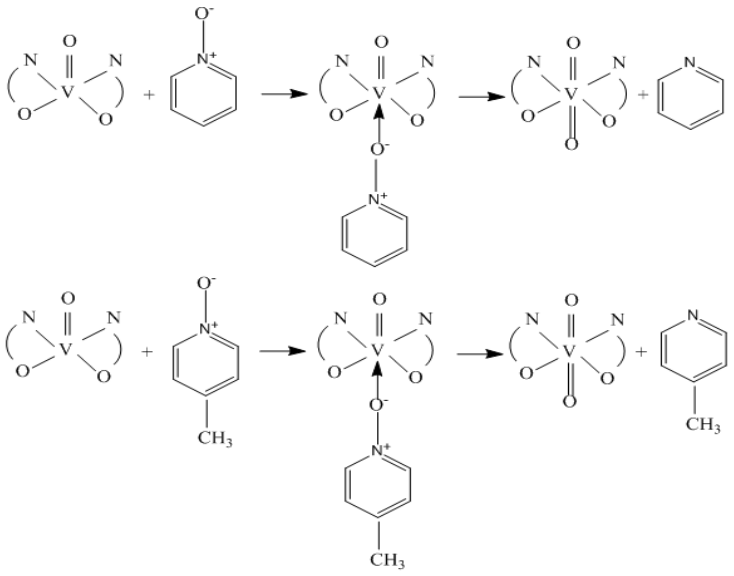
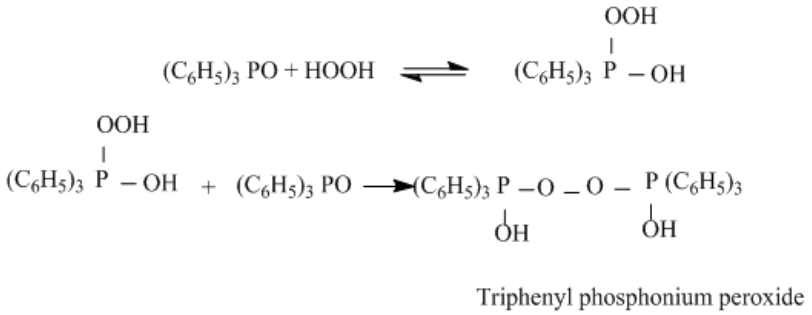


Figure 8 Free base formation from oxo complex and ligand oxide *via* adduct formation.

The adduct between the oxovanadium(IV)-salophen complex and TPPO is not easily formed and is less stable when compared with other LOs, due to the steric hindrance created by the bulky TPPO during the binding with the vanadium metal centre and also due to decrease in electron density on the oxygen atom of TPPO as a result of the presence of three electron withdrawing phenyl group. Since the formation of oxovanadium(IV)- salophen-TPPO adduct is difficult, the reactivity should have been greater in the presence of TPPO than other LOs. However, the reactivity in the presence of added TPPO is found to be very much less and shows least reactivity among the LOs in this reaction series. This unexpected result is quite puzzling and it is really interesting to come across the dichotomous behaviour of TPPO. Milas et al. (1969) in their patented publication of peroxides and peroxy esters and their preparations in the presence of TPPO, have experimentally shown that TPPO forms triphenylphosphonium peroxide with H_2O_2 (Scheme 3).



Scheme 3 Formation of triphenylphosphonium peroxide

Thus concentration of H_2O_2 is decreased which is very essential for the formation of active hydroperoxovanadium species from oxovanadium(IV)-salophen complex. This accounts for the higher rate retardation in the PSAA oxidation catalysed by oxovanadium(IV)-salophen complex and the oxidant H_2O_2 in the presence of TPPO. Among PyO and PicNO, PicNO has more retarding effect and less reactivity than PyO. The lowest rate retarding effect in PyO shows that the weaker binding of PyO with the complex to form the adduct than PicNO. The presence of methyl group in para position of pyridine ring increases the electron density on oxygen of PicNO and this favours the easy formation of oxovanadium(IV)-salophen-PicNO adduct. Due to the greater binding ability of PicNO to form the adduct with the complex more readily, the rate is retarded to a greater extent in the presence of PicNO than that of PyO.

Another possible reason for the rate retardation with LO is the side reaction that may occur during the catalytic oxidation of PSAA i.e., the protonation of free bases formed during the cleavage of N-oxides by the oxidising species (**C_2**) (Bagherzadeh et al, 2008 & Battioni et al. 1988) and conversion of the active peroxo species to an inactive cyclic peroxo species (**C_6**) (Coletti et al 2012). Due to this side reaction, the active species is removed from the reaction mixture followed by the decrease in the concentration of active species which is responsible for the further rate retardation.

CONCLUSION

Owing to the importance of redox reactions in biological system, a mechanistic investigation has been carried out on the oxidative decarboxylation reaction of the therapeutically active phenylsulfinylacetic acid (PSAA) by H_2O_2 with vanadium(IV)-salophen complexes as catalyst , in the presence of ligand oxides. An electrophilic attack of PSAA on the peroxo nucleophilic oxygen atom of the active species formed between the oxidant and catalyst, followed by fast oxygen atom transfer to PSAA has been proposed as the mechanistic pathway for the reaction. The Hammett correlation of the kinetic data of the substituted PSAAs gave a downward curvature while better linearity is observed when the kinetic data were treated with the Yukawa– Tsuno equation. The retardation effect shown by the LOs in all the three oxovanadium(IV)-salophen complexes is found to be TPPO > PicNO > PyO. The observed

order of reactivity, OMe > H > Cl, among substituted oxovanadium(IV)-salophen complexes has been explained on the basis of electronic effects.

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