The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(2): S.I (2), 1028-1040, 2026 www.thebioscan.com

Kinetics and Mechanism of Atenolol Oxidation in Alkaline Permanganate Medium

Sunil B. Hiwale and Rajendra K. Pardeshi *

Department of Chemistry, Sant Ramdas Arts, Commerce & Science College, Ghansawangi, Dist. Jalna, Maharashtra, 431209, India

Corresponding Author: Rajendra K. Pardeshi

Email Address: drrkpardeshi@gmail.com

DOI: https://doi.org/10.63001/tbs.2026.v21.i02.S.I(2).pp1028-1040

KEYWORDS
Atenolol oxidation, Alkaline permanganate, Pseudo-first-order kinetics, Reaction mechanism, Activation parameters.

Received on:
24-04-2026
Accepted on:
11-05-2026
Published on:
22-05-2026

Abstract

The kinetic and mechanistic study of the oxidation of the emerging pharmaceutical contaminant atenolol by alkaline permanganate in a potassium hydroxide medium was conducted spectrophotometrically under pseudo-first-order conditions, utilizing an excess of permanganate. IR spectroscopy was used to find the oxidation product, which proved that the corresponding oxidized derivative of atenolol had formed. The reaction's stoichiometry was 1:2. which means that one mole of atenolol reacts with two moles of Mn(VII). The reaction exhibited pseudo-first-order kinetics concerning permanganate and demonstrated fractional order dependence on both [atenolol] and [OH^-], with each value being less than one. The oxidation happens when an intermediate complex forms between atenolol and the reactive alkaline permanganate species. This complex then breaks down to make the final products. The reaction rate went down when the dielectric constant of the medium went down. This suggests that charged species are involved in the step that sets the rate. We also looked at how ionic strength and the products that were added at first changed things. Kinetic studies conducted at various temperatures facilitated the assessment of activation and thermodynamic parameters.

Introduction

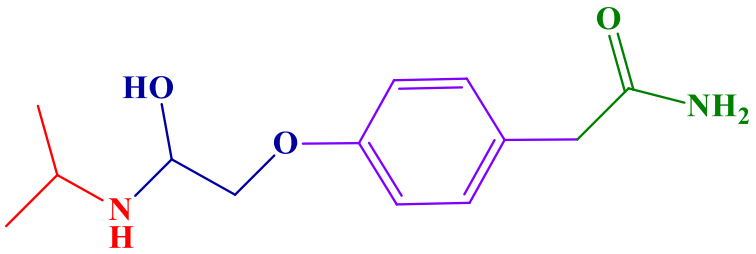
Atenolol is a selective β_1-adrenergic receptor antagonist (beta-blocker) that is commonly used to treat heart problems [1]. It is a cardio-selective beta-blocker because it mostly blocks β_1-receptors in the heart and has very little effect on β_2-receptors in the smooth muscles of the bronchial and vascular systems [2,3]. Atenolol is a safer choice for people with breathing problems than non-selective beta-blockers because it only works on certain types of beta receptors.

Atenolol is frequently prescribed for the management of hypertension, angina pectoris, and cardiac arrhythmias, in addition to the treatment and secondary prevention of myocardial infarction [4,5]. It works by blocking β_1-adrenergic receptors, which lowers the heart rate, myocardial contractility, and cardiac output. This lowers blood pressure and the heart's need for oxygen [2].

Atenolol is relatively hydrophilic in terms of pharmacokinetics, which means it doesn't cross the blood-brain barrier very well. This means that it has fewer side effects on the central nervous system than beta-blockers that are more lipophilic [3]. It

is taken by mouth and has a bioavailability of about 40–50%. The kidneys get rid of most of it unchanged. Atenolol has a half-life of 6 to 9 hours, which makes it easy to take once or twice a day [4].

Atenolol is generally well tolerated; however, it may cause adverse effects, including bradycardia, fatigue, cold extremities, and gastrointestinal disturbances. It should not be used in cases of severe bradycardia, atrioventricular block, or cardiogenic shock. Moreover, caution is imperative for diabetic patients, as atenolol may obscure the manifestations of hypoglycemia [2, 3-15].



Structure of Atenolol

In short, atenolol is still an important and widely used beta-blocker because it works well, is safe, and is not too expensive. However, its use has gone down in some clinical guidelines because newer antihypertensive agents are now available [5-9]. The oxidation of atenolol by permanganate was studied to investigate the kinetics, mechanism, and transformation of atenolol during wastewater treatment by permanganate [10-15].

Materials and Methods:

All chemicals utilized in this study, encompassing potassium permanganate, bases, and salts, were of analytical reagent (A.R.) grade and procured from S. D. Fine Chemicals and Loba Chemicals, located in Chhatrapati Sambhajinagar (Aurangabad), Maharashtra, India. The salts and additional reagents necessary for the examination of ionic strength and medium effects were meticulously prepared utilizing the same double-distilled water to ensure consistency. The atenolol obtained from Lab Trading Pvt. Ltd., located in Chhatrapati Sambhajinagar (Aurangabad), Maharashtra, India, and utilized without additional purification.

Result and Discussion:

1. **Effect of variation of Atenolol (substrate) concentration: -**

The effect of substrate concentration on the oxidation reaction was investigated by changing the concentration of atenolol (from 1×10^{-2}M to 9×10^{-2}M) while keeping the concentration of [$KMnO_4$]=1×10^{-3}M and [KOH]=1M constant. The reaction was carried out under pseudo-first-order conditions, allowing the determination of the corresponding pseudo-first-order rate constants.

The experimental results showed that the pseudo-first-order rate constants increased with the increase of atenolol concentration, but not in a strict proportional way. A plot of initial rate against atenolol concentration was a straight line with a positive slope (**Figure 1**) indicating that the rate of reaction is dependent on substrate concentration. Furthermore, the plot of [atenolol] vs. k showed that the reaction is of fractional-order with respect to atenolol.

The concentration of atenolol was varied from 1×10^{-2}M to 9×10^{-2} M and the effect on the pseudo-first-order rate constant (k) was studied. Results indicated that k increased from 1.45 x 10^{-2} to 2.42 x 10^{-2} with increasing atenolol concentration. But the increase was not proportional, because doubling or tripling the substrate concentration did not result in a corresponding increase in k. This behavior indicates that the reaction obeys pseudo-first-order kinetics and shows fractional-order dependence on the concentration of atenolol.

As the reaction has been deliberated under pseudo-first order condition using equation,

$$k = \frac{2.303}{t}\log\frac{a}{a-x}$$

Which is reformed as;

$$k = \frac{2.303}{t}\log\frac{(OD)_\infty - (OD)_0}{(OD)_\infty - (OD)_t}$$

2. Effect of variation of $KMnO_4$ (oxidant) concentration: -

To evaluate and study the effect of variation of oxidant, the concentration of $KMnO_4$ was varied in the range of 1 x 10^{-3} M to 9 x 10^{-3} M. The information in **Figure 2** shows how changing the oxidant concentration [$KMnO_4$] affects the pseudo-first-order rate constant for the oxidation of Atenolol at 35 ± 0.5 °C. The concentrations of Atenolol (9 × 10^{-2} M) and KOH (1 M) remained the same. The rate constant (k) goes up as the concentration of $KMnO_4$ goes up, especially when the oxidant is at lower concentrations. This shows that the reaction rate is affected by how many permanganate ions are present in the reaction medium. This suggests that $KMnO_4$ is directly involved in the rate-determining step under pseudo-first-order conditions.

But at higher levels of $KMnO_4$, the trend isn't perfectly linear, as shown by the k values changing. This behavior could be due to things like the formation of intermediate complexes, changes in ionic strength, or possible secondary reactions happening when the oxidant concentration is high. Even though there are some small differences, the overall trend shows that the reaction rate depends positively on the concentration of oxidant. This means that the reaction shows first-order dependence with respect to $KMnO_4$ under the given experimental conditions.

3. Effect of variation of KOH concentration: -

To study the effect of variation changing the amount of potassium hydroxide (KOH) on the pseudo-first-order rate constant for the oxidation of Atenolol at 35 ± 0.5 0C. We were able to do this while keeping the concentrations of Atenolol (9×10^{-2} M) and $KMnO_4$ (3×10^{-3} M) the same. We found that the rate constant tends to go up when the concentration of KOH goes up, especially when the concentrations are between low and medium.

This pattern suggests that hydroxide ions are very important for speeding up the reaction. This could be true because they either make the oxidant more reactive or

help to stabilize the intermediate species that form during the reaction.

Also, the fact that the rate constant generally goes up as [KOH] goes up means that the reaction rate has a positive effect on base concentration. Even though there are some small changes in k values that can be seen at certain concentrations, this is still true.

This investigation supports the conclusion that the reaction follows first-order kinetics with respect to KOH under pseudo-first-order conditions. Also, the linear relationship that came from the plot of starting rate vs. [KOH] with a positive slope gives more proof that the base is involved in the step that sets the rate, which has a big effect on how the reaction happens (**Figure 3**).

4. Effect of variation of temperature: -

The effect of temperature was studied keeping constant concentration of all reactants such as [$KMnO_4$] = 3 x 10^{-3} M, [Atenolol] = 9 x 10^{-2} M and [KOH] = 1 M. The temperature variation was varied in the range of 35^0 °C to 600 °C (**Figure 4**). The energy of activation was calculated by plotting log k versus 1/T, a straight line was obtained (**Figure 5**). The temperature dependence of the rate constant can be given as,

$$k = \frac{k_B}{T} e^{\frac{\Delta Ea^{\#}}{RT}} e^{\frac{\Delta S^{\#}}{R}}$$

The modest enthalpy of activation and higher rate constant of slow step indicate that the oxidation presumably occurs by an inner sphere mechanism. The free energy change (ΔG), enthalpy changes (ΔH) and entropy change (ΔS) was determined.

The thermodynamic parameters for the oxidation of atenolol were evaluated over the temperature range of 298–328 K. The rate constant (k) was observed to increase progressively from 0.0487 to 0.0589 with rise in temperature, indicating that the reaction is temperature-dependent and follows Arrhenius behavior. The calculated activation energy (Ea = 7340.51 J mol^{-1}) supports the requirement of energy input for the reaction to proceed. The enthalpy change (ΔH) values are positive throughout the temperature range, confirming the endothermic nature of the reaction, although a slight decrease in ΔH with increasing temperature suggests improved interaction between reacting species. **Figure 6** confirmed that the variation in ΔS vs ΔH.

The entropy change (ΔS) values are negative, indicating a decrease in randomness and the formation of a more ordered activated complex, which may be attributed to intermediate complex formation during the oxidation process. The Gibbs free energy change (ΔG) values are positive and increase with temperature, revealing that the reaction is non-spontaneous under the studied conditions. Overall, the reaction is kinetically favored at higher temperatures but thermodynamically non-spontaneous, suggesting a controlled mechanism involving an ordered transition state.

5. Effect of variation of solvent concentration: -

The reaction was monitored in three different solvents, namely acetone, ethyl acetate, and n-hexane. The rate constants for acetone were found to be less compared to other solvents. Table 5.1.7 shows how the composition of the solvent affects the

pseudo-first-order rate constant for the oxidation of Atenolol at 35 ± 0.5 °C, while keeping the concentrations of Atenolol (9 × 10^{-2} M), $KMnO_4$ (3 × 10^{-3} M), and KOH (1 M) the same.

It is clear that the rate constant changes a lot when the type and amount of solvent change. In the solvents that were looked at, n-hexane usually has higher rate constant values than acetone and ethyl acetate, especially when the solvent composition is low to medium. This indicates that environments with less polar solvents enhance the reaction rate, likely due to diminished solvation of reactant species and increased interaction between the oxidant and substrate.

On the other hand, polar solvents like acetone and ethyl acetate have rate constants that are lower or change more often. This shows that the polarity of the solvent has a big effect on the reaction kinetics. The changes in rate constants with different solvent compositions may be due to changes in the dielectric constant, solvation effects, and the stabilization of intermediate species during the reaction.

The pseudo-first-order rate constant for atenolol oxidation is significantly affected by the solvent type and solvent composition, as shown in **Figure 7(a–c)**. Acetone showed moderate changes in rate constants among the solvents studied, and the maximum rate constant was obtained at 10% solvent composition. At low acetone concentrations, the rate increase might be due to better solvation of reactants and transition-state species. In the presence of higher acetone concentrations, however, the effective ionic interactions between permanganate and hydroxide ions are likely to be decreased.

Ethyl acetate showed relatively lower and irregular rate constants due to its lower polarity and dielectric constant. The maximum rate was obtained at 20% composition, after which the reaction rate decreased or remained almost constant. This behavior indicates weaker stabilization of charged intermediates and competing effects of solvation and dilution.

By contrast, n-hexane had the highest rate constants, especially at low and intermediate solvent compositions. The increase in reactivity in a non-polar medium could be attributed to decreased solvation of ionic species and strong hydrophobic interactions with atenolol. However, the rate decreased significantly at 100% n-hexane because of poor reactant solubility and the lack of support for ionic reactions. Overall, the oxidation rate was enhanced with decreasing solvent polarity until an optimum composition was achieved.

6. Effect of variation of salts: -

To study the effect of variation of salts, the concentration of salts was varied from 1 x 10^{-2}M to 9 x 10^{-2}M, keeping constant concentration of reactants such as [$KMnO_4$] = 3 x 10^{-3}M, [Atenolol] = 9 x 10^{-2}M, [KOH] = 1M. From the obtained results, it is clear that pseudo first order rate constant kobs increase with the increase in concentration of salts. A plot of log k_{obs} vs $\Delta\mu$, according to extended Bronsted Debye-Huckel equation was found to be linear with positive slopes (KBr, KCl, NaCl, KNO_3 and $CaCl_2$) indicating positive salt effect. (**Figure 8(p-t)**)

The information about how adding salts (KBr, KCl, NaCl, KNO_3, $CaCl_2$, and KOH) changes the pseudo-first-order rate constant

shows that the ionic environment has a big effect on the reaction rate. The rate constants don't stay the same as the salt concentration goes up (0.01–0.10 M); instead, they change in a small but steady way. $CaCl_2$ has the highest rate constant values of all the salts studied, no matter how concentrated they are. This means that it has a bigger effect on how fast the reaction happens. This could be because the ionic charge (Ca^{2+}) is higher, which changes the ionic strength of the medium a lot and makes the reactant species less active.

Proposed Reaction Mechanism of Atenolol:

Step I: Formation of Reactive Permanganate Species (Fast Equilibrium):

In alkaline medium, permanganate interacts with hydroxide ions to form an activated species:

$$MnO_4^- + \bar{O}H \underset{}{\overset{K_1}{\rightleftharpoons}} \left[MnO_4.OH\right]^{2-}$$

Step II: Formation of Intermediate Complex (Fast Equilibrium)

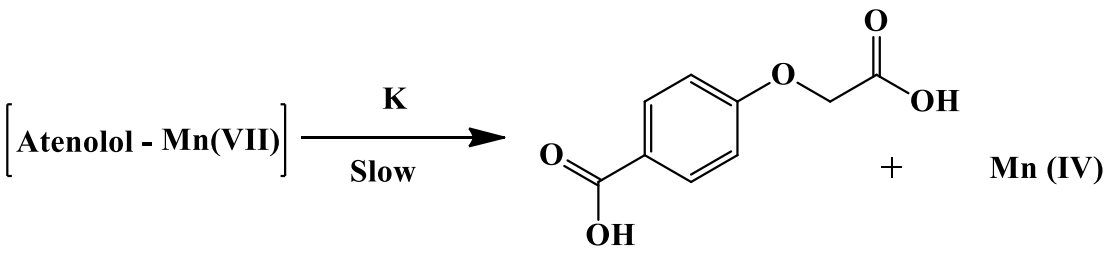
The activated permanganate species interacts with atenolol to form a coordination complex:

$$\left[MnO_4.OH\right]^{2-} + \text{Atenolol} \overset{K_2}{\rightleftharpoons} \left[\text{Atenolol - Mn(VII)}\right] \text{ Complex}$$

This step involves coordination through the hydroxyl or amino functional group of atenolol.

Step III: Electron Transfer and Decomposition (Slow Step)

The complex undergoes slow electron transfer, leading to bond cleavage and oxidation:



Product

The slow breakdown of the Atenolol–Mn intermediate complex (**Step III**) is what makes the reaction go faster. There are a few important things that this assignment is based on. First, this step includes important steps like bond cleavage and electron transfer, which need more energy than simple association or equilibrium steps.

Second, the fact that these changes need a lot of activation energy to happen makes it even more likely that they happen more slowly than other steps in the mechanism. Also, kinetic studies show that

when permanganate is present in large amounts, the reaction rate does not depend on its concentration.

$$[MnO_4^-] = [MnO_4^-] + [HMnO_4^{2-}]$$

$$= [MnO_4^-] + K[MnO_4^-]\,[OH^-]$$

$$= [MnO_4^-]\,\{1+K_1[OH^-]\}$$

$$K = \frac{K_2\,K\,[Atenolol][MnO_4^{-2}]}{1 + K_1[OH^-]}$$

$$\frac{Rate}{[MnO_4^-][Atenolol]} = \frac{K\,K_2}{1 + K_1[OH^-]}$$

$$\therefore \frac{\mathbf{1}}{\boldsymbol{K_{Obs}}} = \frac{\mathbf{1}}{K\,K_2} + \frac{K_1[OH^-]}{K\,K_2}$$

Hence, the rate expression is verified by plotting $1/K_{obs}$ against [KOH], a strength line is observed. Under conditions of excess oxidant, the oxidation of atenolol by alkaline potassium permanganate follows pseudo–first-order kinetics. The reaction goes through the formation of an intermediate Atenolol–Mn complex, which breaks down slowly and sets the rate of the reaction. The derived rate law and kinetic behavior align well with experimental results, suggesting that the reaction proceeds via a complex-mediated pathway. These findings provide robust evidence for an inner-sphere electron transfer mechanism, in which the coordination between atenolol and permanganate enhances the oxidation process.

Infra-red Spectroscopy:

The FT-IR spectrum of the product 4-(carboxymethoxy)benzoic acid showed several characteristic absorption bands that confirmed the presence of the functional groups in the proposed structure (**Table 1**).

Table 1: Infra-red spectroscopic values of 4-(carboxymethoxy)benzoic acid

Sr. No.	Wavenumber (cm^{-1})	Assignment	Functional Group Explanation
1.	3485 cm^{-1}	O–H stretching	Broad peak corresponding to carboxylic acid O–H stretching
2.	3242 cm^{-1}	Hydrogen-bonded O–H stretch	Additional –COOH hydrogen bonded O–H vibration
3.	3033 cm^{-1}	Aromatic C–H stretch	Indicates benzene ring C–H stretching
4.	2845 cm^{-1}	Aliphatic C–H stretch	Due to $–CH_2–$ groups attached to aromatic ring

5.	1685 cm^{-1}	C=O stretching	Carbonyl stretching of carboxylic acid (–COOH)
6.	1500 cm^{-1}	Aromatic C=C stretching	Characteristic benzene ring skeletal vibration
7.	1335 cm^{-1}	C–O stretching	C–O stretch of carboxylic acid / ether linkage
8.	993 cm^{-1}	Aromatic C–H bending	Out-of-plane bending of aromatic C–H
9.	916 cm^{-1}	Aromatic substitution band	Indicates substituted benzene ring

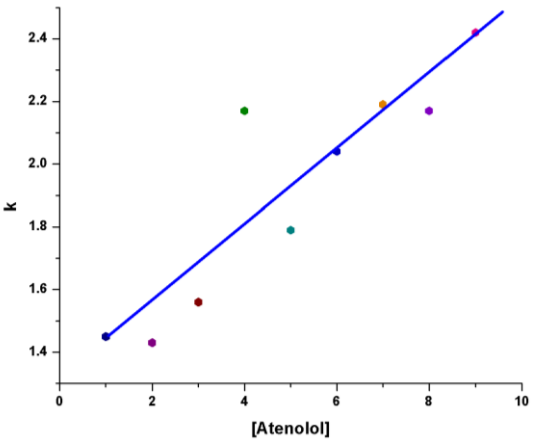


Fig. 5.1.1: Variation of [Atenolol]

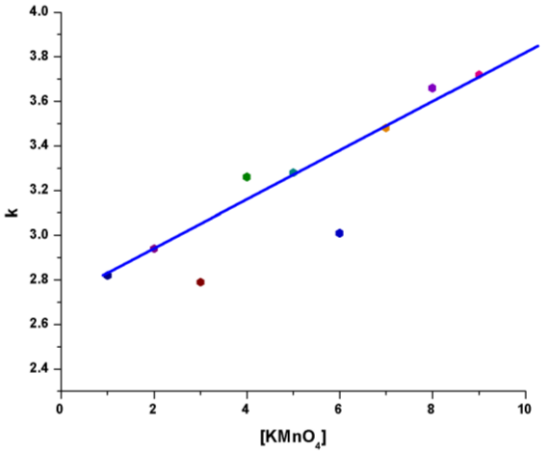


Figure 5.1.2: Variation of [$KMnO_4$]

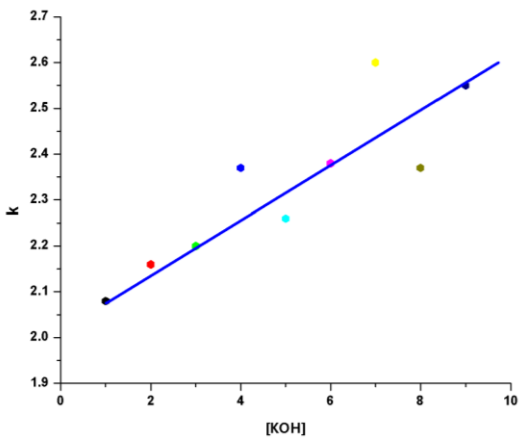


Figure 5.1.3: Variation of [KOH]

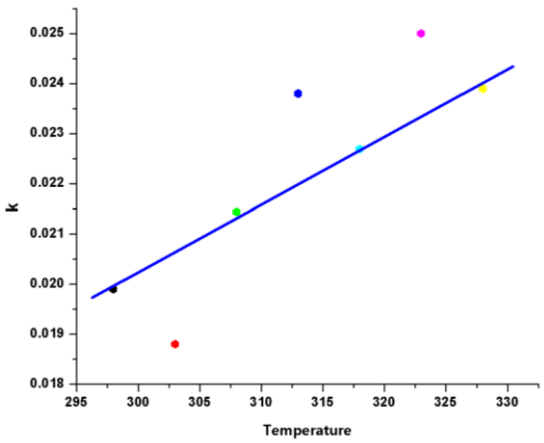


Figure 5.1.4: Effect of Temperature

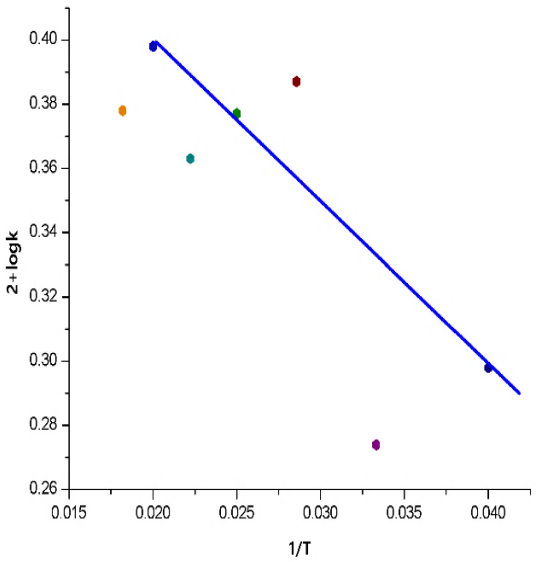


Figure 5.1.5: 2+logk Vs 1/T

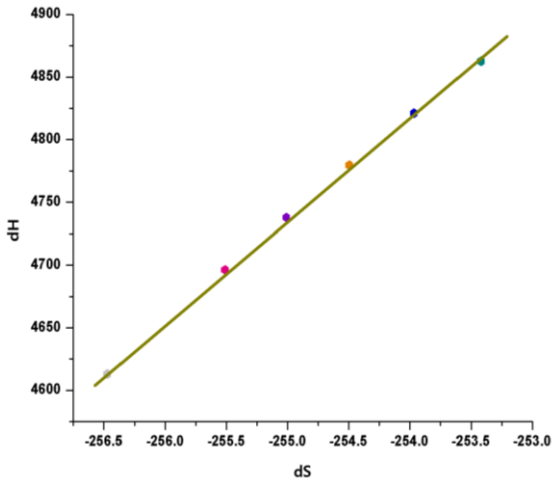
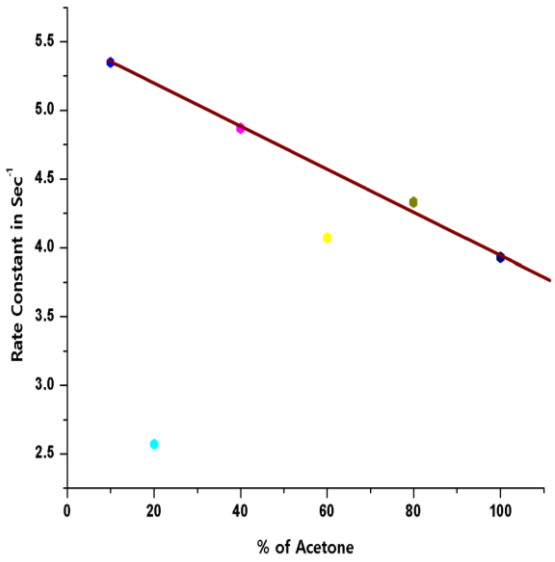
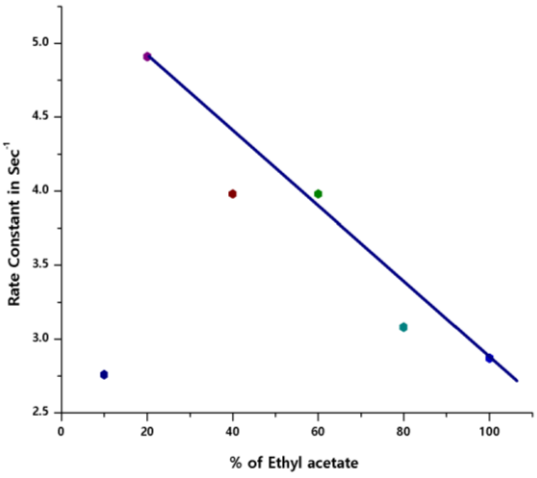


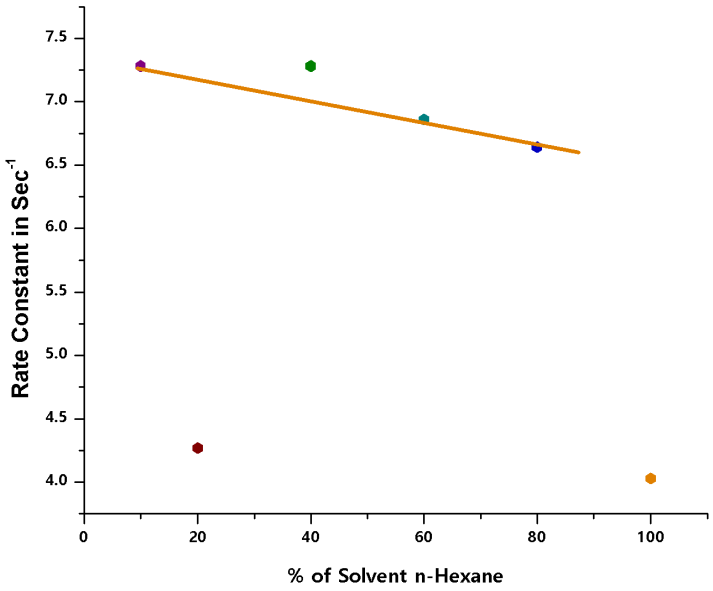
Figure 5.1.6: Variation of ΔH Vs ΔS



(a)

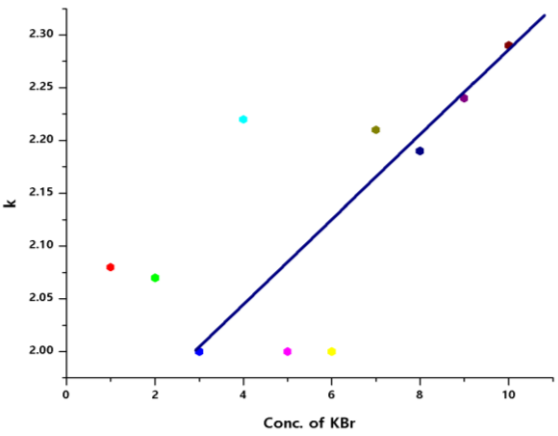


(b)

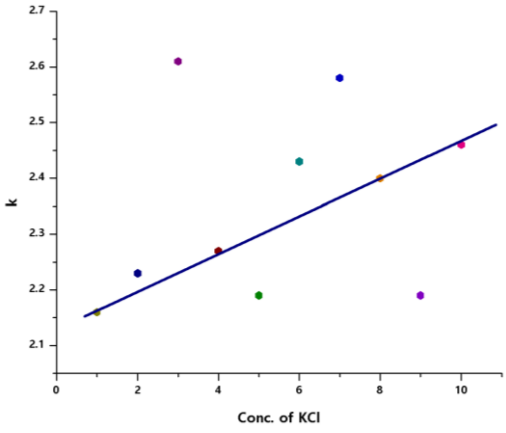


(c)

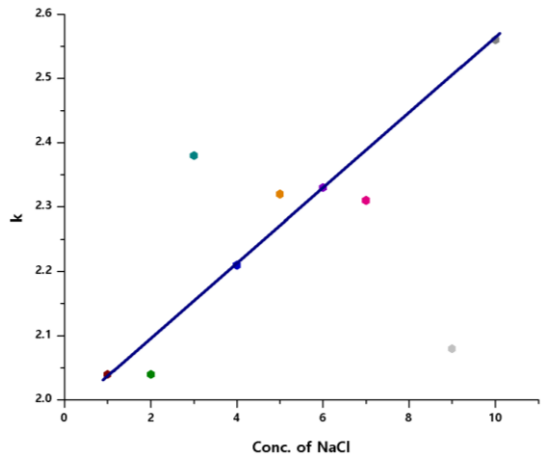
Figure 5.1.7: Variation of rate constant with solvent (a) Acetone (b) Ethyl acetate (c) n-Hexane



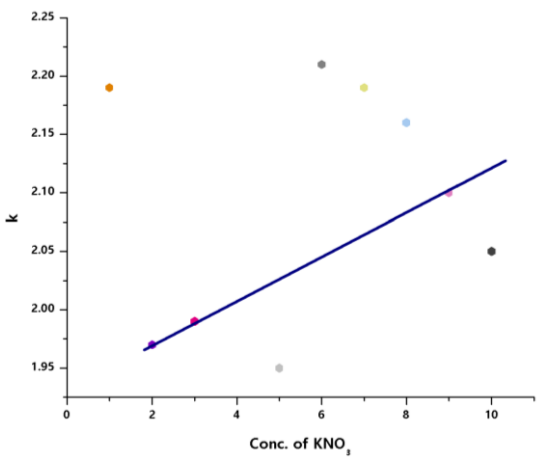
(p)



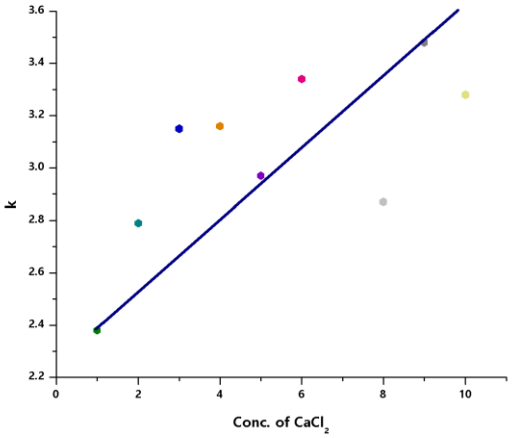
(q)



(r)



(s)



(t)

Figure 5.1.8: Variation of rate constant with concentration of salt (p) KBr (q) KCl (r) NaCl (s) KNO_3 (t) $CaCl_2$

Conclusion

The present study deals with the oxidation kinetics of atenolol by alkaline potassium permanganate under pseudo-first-order conditions. The reaction rate was found to increase with the increase in the concentrations of atenolol, KMnO4, KOH, temperature and added salts confirming the significant influence of substrate, oxidant, base and ionic strength on the oxidation process. The dependence upon atenolol was fractional-order and the dependence upon oxidant and hydroxide ion concentrations was first-order. Temperature studies indicate that the reaction obeys Arrhenius behavior and occurs via an endothermic, nonspontaneous pathway involving an ordered activated complex. The solvent studies revealed that the reaction rate increased to an optimum composition in the less polar media, especially in n-hexane,

due to reduced solvation effects and enhanced substrate–oxidant interactions. Studies on kinetics and mechanism supported the formation of an intermediate Atenolol-Mn complex, the slow decomposition of which is the rate-determining step. Overall oxidation is believed to occur via an inner-sphere electron transfer mechanism. FT-IR spectral analysis of the product confirmed the formation of 4-(carboxymethoxy) benzoic acid as the oxidation product.

Conflict of Interest:

The authors declare that they have no conflict of interest.

References:

[1] Hernández, R. H., Armas-Hernández, M. J., Velasco, M., Israili, Z. H., & Armas-Padilla, M. C. (2003). Calcium antagonists and atherosclerosis protection in hypertension. *American Journal of Therapeutics, 10*(6), 409–414.

[2] Katzung, B. G., & Vanderah, T. W. (2022). *Farmacologia básica e clínica*. Artmed Editora.

[3] Rang, H. P., Dale, M. M., Ritter, J. M., Flower, R. J., & Henderson, G. (2011). *Rang & Dale's pharmacology*. Elsevier Health Sciences.

[4] Ugosor, P. T., and S. T. Wada. "Antimicrobial studies of biosynthesized zinc oxide nanoparticles." *Microbiol Archives Int J* 10 (2025).

[5] Sweetman, S. C. (Ed.). (2009). *Martindale: The complete drug reference* (Vol. 1). Pharmaceutical Press.

[6] Whelton, P. K., Carey, R. M., Aronow, W. S., Casey, D. E., Collins, K. J., Dennison Himmelfarb, C., DePalma, S. M., Gidding, S., Jamerson, K. A., Jones, D. W., MacLaughlin, E. J., & others. (2017). 2017 ACC/AHA/AAPA/ABC/ACPM/ AGS/APhA/ASH/ASPC/NMA/P CNA guideline for the prevention, detection, evaluation, and management of high blood pressure in adults: A report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. *Journal of the American College of Cardiology, 71*(19), e127–e248.

[7] Izam, Y. Y. (2026). Koshoedo Senapon John From Antioxidants to Survival: Multifaceted Bioactivities of the Bark and Leaf of Eucalyptus Globulus Extracts in Drosophila Melanogaster". *Acta Pharma Reports*.

[8] Shetti, P., Singh, S., Kumbar, V., Dodamani, S., Paranjape, R., & Kubade, M. (2025). Understanding the Therapeutic Versatility of Apigenin and Quercetin: Broad Applications in Health and Wellness. *Acta Pharma Report*

[9] Ghutke, Tejal Dharmraj, Rushabh Gajanan Kadam, and M. Vineeth. "Impact of Organic Additives on Enzymatic Antioxidant Activities in Lentinus edodes Shiitake Mushroom." *Environmental Reports; an International Journal* 13 (2023).

[10] Anayeokwu, S. N., Ikomi, R. B., Ogidiaka–Obende, E., &

Omoarebun, E. J. (2026). Ecological Signi icance of Aquatic Life in Hydrothermal Vents in Ocean
Ecosystems. *Environmental Reports; an International Journal*.

[11] Harrison, E. O., & Melford, C. M. (2026). Multisystem Biochemical Toxicity in Experimental Rats: Evidence from Hepatic, Renal, Lipid, Oxidative, and Reproductive Indices. *Journal of American Medical Science and Research. DOI: https://doi. org/10.51470/AMSR*, *1*.

[12] Sultana, N., Saini, P. K., Kiran, S. R., & Kanaka, S. (2023). Exploring the antioxidant potential of medicinal plant species: A comprehensive review. *Journal of Plant Biota*, *2*(2), 9-18.

[13] Zaheer, J. (2025). Mechanism of Endothelial Dysfunction in Hypertension: Nanotechnology-Based Interventions. *Acta Pharma Reports*.

[14] Daksha, Karthikeyan, Rajan Radha Rasmi, Kanakaraj Suganya, Kunnathur Murugesan Sakthivel, D. S. R. S. Kumar, Sankar Soundariya, and Mythili Saravanan. "Nanostructured therapeutics in inlammation-associated cancer: from molecular design to clinical potential." *J Am Med Sci Res* 4, no. 1 (2025): 20-30.

[15] Adebisi, Olusoji Olusegun, Tayo Modupe Kayode-Isola, Ifeoluwa Deborah Gbala, and Emmanuel Adukwu. "Impact of hydrogen peroxide tolerance on carbapenem susceptibility in bacteria isolated from poultry environments." *Microbiol Archives Int J* (2025).