

Oxidation of Caffeine by Permanganate Ion in Perchloric and Sulfuric Acids Solutions: A Comparative Kinetic Study

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Abstract: The kinetics of oxidations of caffeine by permanganate ion in both perchloric and sulfuric acids solutions have been investigated spectrophotometrically at a constant ionic strength of 1.0 mol dm^{-3} and at 25°C . In both acids, the reaction-time curves were obtained with a sigmoid profile suggesting an autocatalytic effect caused by Mn(II) ions formed as a reaction product. Both catalytic and non-catalytic processes were determined to be first order with respect to the permanganate ion and caffeine concentrations, whereas the orders with respect to $[\text{H}^+]$ and $[\text{Mn(II)}]$ were found to be less than unity. Variation of either ionic strength or dielectric constant of the medium had no significant effect on the oxidation rates. Spectroscopic studies and Michaelis-Menten plots showed no evidence for the formation of intermediate complexes in both acids suggesting that the reactions point towards the outer-sphere pathway. The reactions mechanism adequately describing the kinetic results was proposed. In both acids, the main oxidation products of caffeine were identified as 1,3,7-trimethyluric acid. Under comparable experimental conditions, the oxidation rate of caffeine in perchloric acid was slightly higher than that in sulfuric acid. The constants involved in the different steps of the reactions mechanism have been evaluated. With admiration to the rate-limiting step of these reactions, the activation parameters have been evaluated and discussed.

Keywords: Caffeine, Oxidation, Permanganate, Acid, Kinetics, Mechanism

1. Introduction

Alkaloids are a group of naturally occurring chemical compounds that act on a diversity of metabolic systems in humans and other animals. They are produced by a large variety of organisms including bacteria, fungi, plants, and animals. Alkaloids have a wide range of pharmacological activities including antimalarial, antiasthma, anticancer, cholinomimetic, antibacterial, psychotropic and stimulant activities [1-3]. Among the significant alkaloids is caffeine which is a member of the purine alkaloid group of metabolites widely found in the leaves and fruits of many types of plants [4]. Caffeine (1,3,7-trimethylxanthine) is one of the most popular and commercially important plant derived purine alkaloids. It is also one of the most commonly

used legal pharmaceutical drugs throughout the world, being present in foods, beverages, including coffee, tea, soft drinks, energy drinks and medicines [5]. It is a key additive to at least 150 other products that are available currently in the market. Caffeine is a central nervous system and metabolic stimulant [6, 7], used to reduce physical fatigue and to prevent or treat drowsiness. It has the desired effect of delaying/preventing sleep and also improves performance during sleep deprivation [8]. In athletes, moderate doses of caffeine can improve sprint [9], stamina, endurance [10], and team sports performance [11], but the improvements are usually limited. At normal doses, caffeine improves memory in learning and sleep deprived activities, but has both beneficial and harmful effects on the working memory depending on the nature of the task [12]. Caffeine has been

the subject of extensive research in recent years [13] because of its wide spread occurrence in nature [4], their long-standing history of human consumption, possibly since the Stone Age [14], its physiological effects, and its applicability in foods, drugs and cosmetics [5].

Oxidation reactions are very important in organic synthesis. Among the important oxidizing agents, permanganate ion is widely used in the oxidations of many organic compounds in neutral, alkaline and acidic media [15-25]. The mechanism of oxidation reactions by permanganate ion is governed by pH of the medium [26]. During oxidation by permanganate, it is evident that the Mn(VII) in permanganate is reduced to various oxidation states in acid, alkaline and neutral media. In acid media, permanganate ion (MnO_4^-) can exist in several different forms, HMnO_4 , H_2MnO_4^+ , HMnO_3 , and Mn_2O_7 depending on the nature of the reductant. The oxidant has been assigned with an inner-sphere and an outer-sphere mechanism pathways in their redox reactions [27, 28].

A literature survey revealed that there are very few reports [29-31] describing the mechanism of oxidation of caffeine, which may be important from a metabolic point of view. Furthermore, caffeine oxidation could lead to novel bioprocesses to produce commercially important derivatives which may be applicable in cosmetics and medicines. In view of the foregoing aspects, we prompted to undertake the present investigation of the kinetics and mechanism of oxidations of caffeine by permanganate ion as the most efficient and eco-friendly oxidizing agent in different acid media. The objectives of the present study are to check the reactivity of caffeine towards permanganate ion in acid media, and to propose the oxidation mechanism of such drug to understand its mode of action in biological systems.

2. Experimental

2.1. Materials

All chemicals used in this work were of reagent grade and their solutions were prepared by dissolving the required amounts of the samples in doubly distilled water. The stock solution of caffeine was prepared by dissolving the sample (Sigma-Aldrich) in doubly distilled water. Potassium permanganate freshly solution was prepared and standardized as reported earlier [32]. Sodium perchlorate and acetic acid were used to attain the required ionic strength and dielectric constant of the reactions medium, respectively.

2.2. Kinetic Measurements

The kinetic measurements were followed under pseudo-first order conditions where caffeine was existed in a large excess over that of permanganate. Initiation of the reactions were done by mixing the formerly thermostatted solutions of permanganate and caffeine that also contained the required amounts of the acid and NaClO_4 . The courses of the reactions were followed by monitoring the decay in the absorbance of permanganate as a function of time at its absorption

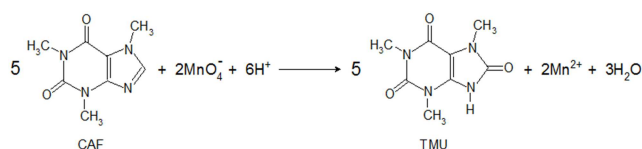
maximum ($\lambda = 525 \text{ nm}$), whereas the other constituents of the reaction mixtures did not absorb considerably at this wavelength. The absorption measurements were done in a temperature-controlled Shimadzu UV-VIS-NIR-3600 double-beam spectrophotometer. Application of Beer's law was verified for permanganate concentrations at $\lambda = 525 \text{ nm}$, and the molar extinction coefficient was found to be $\epsilon = 2230 \pm 45 \text{ dm}^3 \text{ mol}^{-1} \text{ cm}^{-1}$.

The orders of the reactions with respect to the reactants were determined from the slopes of the $\log k_s$ and $\log k_f$ versus $\log(\text{concentration})$ plots, where k_s and k_f refer to the pseudo-first order rate constants of the slow (induction) and fast (auto-acceleration) periods, by varying the concentrations of caffeine and acids, in turn, while keeping other conditions constant.

3. Results

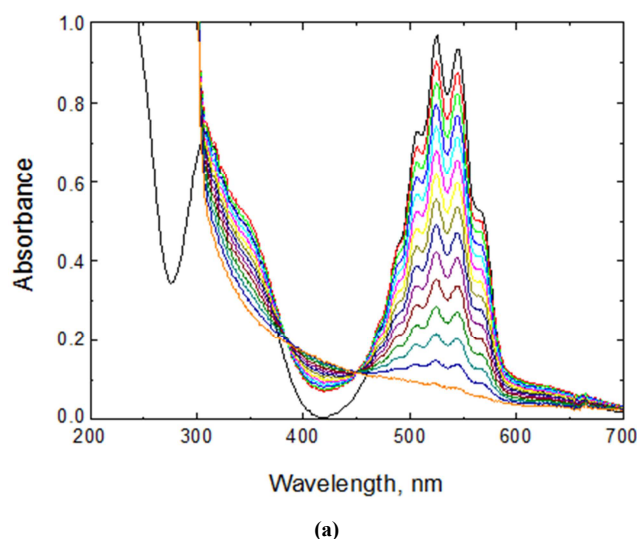
3.1. Stoichiometry and Product Characterization

Reaction mixtures containing various amounts of permanganate ion and caffeine at constant $[\text{H}^+]$, ionic strength, and temperature were allowed to react for 24 h in closed vessels for completion of the oxidation reactions. The unconsumed [permanganate] was determined spectrophotometrically at 525 nm. The results indicated that four moles of permanganate are consumed by five mole of caffeine to yield the oxidation products as shown in the following equation,



where CAF and TMU denotes caffeine and its oxidation product, 1,3,7-trimethyluric acid which was identified by HPLC analysis. Similar oxidation product of caffeine was reported earlier [32].

3.2. Spectral Changes



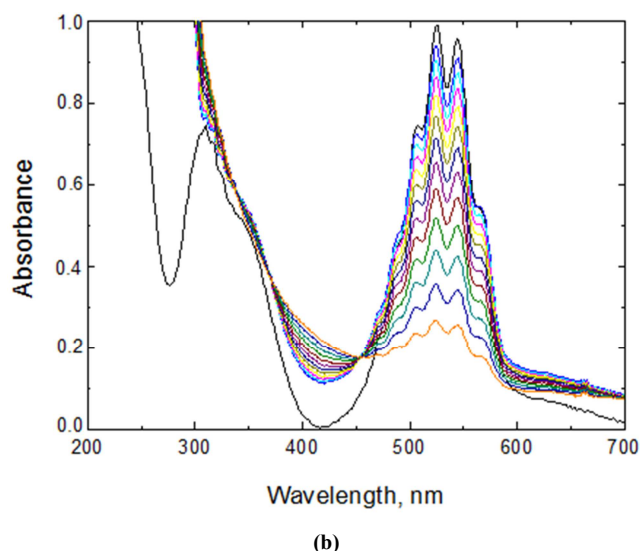


Figure 1. Spectral changes during the oxidations of caffeine by permanganate ion in: (a) perchloric, and (b) sulfuric acid solutions. $[CAF] = 1.0 \times 10^{-2}$, $[MnO_4^-] = 4.0 \times 10^{-4}$, $[H^+] = 0.5$ and $I = 1.0 \text{ mol dm}^{-3}$ at 25°C . Scanning time intervals = 2.0 min.

The spectral scans during the oxidation of caffeine by permanganate ion in perchloric and sulfuric acids solutions are shown in Figure= 1 (a) and (b), respectively. It was shown that there are gradual disappearance of permanganate band at its absorption maximum ($\lambda = 525 \text{ nm}$). Figure 1 shows also a simultaneous appearance of a new band at a wavelength of 418 nm with two isosbestic points located in the region of 370 – 450 nm.

3.3. Reaction–Time Curves

Table 1. Effect of variation of $[MnO_4^-]$, $[CAF]$, $[H^+]$ and I on the pseudo-first order rate constants in the oxidations of caffeine by permanganate ion in perchloric and sulfuric acids solutions at 25°C .

| $10^4[MnO_4^-]$ (mol dm ⁻³) | $10^2 [CAF]$ (mol dm ⁻³) | $[H^+]$ (mol dm ⁻³) | I (mol dm ⁻³) | Perchloric | | Sulfuric | |
|--|---|------------------------------------|--------------------------------|----------------------------|----------------------------|----------------------------|----------------------------|
| | | | | $10^3 k_s (\text{s}^{-1})$ | $10^3 k_f (\text{s}^{-1})$ | $10^3 k_s (\text{s}^{-1})$ | $10^3 k_f (\text{s}^{-1})$ |
| 2.0 | 1.0 | 0.6 | 1.0 | 21.2 | 32.0 | 19.1 | 28.3 |
| 4.0 | 1.0 | 0.6 | 1.0 | 22.1 | 32.6 | 18.9 | 27.2 |
| 6.0 | 1.0 | 0.6 | 1.0 | 23.9 | 34.1 | 18.4 | 26.3 |
| 8.0 | 1.0 | 0.6 | 1.0 | 21.9 | 32.5 | 20.2 | 27.1 |
| 10.0 | 1.0 | 0.6 | 1.0 | 22.4 | 31.7 | 18.0 | 27.9 |
| 4.0 | 0.2 | 0.6 | 1.0 | 5.5 | 7.3 | 4.5 | 6.7 |
| 4.0 | 0.6 | 0.6 | 1.0 | 13.1 | 17.9 | 12.0 | 16.2 |
| 4.0 | 1.0 | 0.6 | 1.0 | 22.1 | 32.6 | 18.9 | 27.2 |
| 4.0 | 1.4 | 0.6 | 1.0 | 30.4 | 43.8 | 25.2 | 37.1 |
| 4.0 | 1.8 | 0.6 | 1.0 | 36.2 | 54.3 | 33.0 | 46.0 |
| 4.0 | 1.0 | 0.1 | 1.0 | 6.2 | 9.1 | 5.2 | 7.2 |
| 4.0 | 1.0 | 0.3 | 1.0 | 14.7 | 20.2 | 12.1 | 17.0 |
| 4.0 | 1.0 | 0.5 | 1.0 | 22.1 | 32.6 | 18.9 | 27.2 |
| 4.0 | 1.0 | 0.7 | 1.0 | 29.7 | 42.8 | 25.6 | 35.7 |
| 4.0 | 1.0 | 0.9 | 1.0 | 38.2 | 51.7 | 31.5 | 42.9 |
| 4.0 | 1.0 | 0.6 | 1.0 | 22.1 | 32.6 | 18.9 | 27.2 |
| 4.0 | 1.0 | 0.6 | 1.3 | 23.1 | 33.6 | 20.2 | 28.2 |
| 4.0 | 1.0 | 0.6 | 1.6 | 22.9 | 33.1 | 18.4 | 29.1 |
| 4.0 | 1.0 | 0.6 | 1.9 | 21.0 | 31.2 | 19.2 | 28.9 |
| 4.0 | 1.0 | 0.6 | 2.2 | 22.4 | 31.9 | 21.7 | 29.1 |

Experimental error $\pm 3\%$

The reaction time curve describing the double-stage time courses during the oxidation of caffeine by permanganate ion in, for example, perchloric acid medium is illustrated in Figure 2. The curve was sigmoid where the initial stage was slow, followed by an increase in the oxidation rate over longer time periods. The pseudo-first order rate constants, k_s and k_f , were calculated using non-linear least-squares fitting to the first order dependence of the absorbance versus time plots. The rate constants were the main values of at least two kinetic measurements. The rate constants were reproducible to within 3-4%.

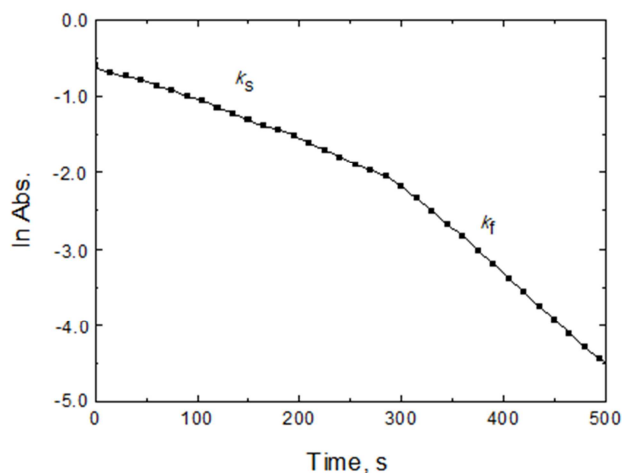


Figure 2. Reaction-time curve for the oxidation of caffeine by permanganate ion in perchloric acid medium. $[CAF] = 0.01$, $[MnO_4^-] = 4.0 \times 10^{-4}$, $[H^+] = 0.1$, and $I = 1.0 \text{ mol dm}^{-3}$ at 25°C .

3.4. Rate Dependence on Permanganate Ion Concentration

Permanganate ion oxidant was varied in the concentration range $(2.0 - 10.0) \times 10^{-4} \text{ mol dm}^{-3}$ while the rest of the reactant concentrations were kept constant. Both pH and temperature were also kept constant. Variation of the initial concentration of permanganate showed almost no influence on the pseudo-first order rate constants (k_s & k_f) as listed in Table 1, indicating first order dependence with respect to permanganate ion concentration.

3.5. Rate Dependence on Caffeine Concentration

The pseudo-first order rate constants were measured at various concentrations of caffeine keeping others constant. Plots of k_s and k_f versus [CAF] were found to be linear passing through origin in both perchloric and sulfuric acid solutions as shown in Figure 3 confirming first order dependence with respect to caffeine concentration.

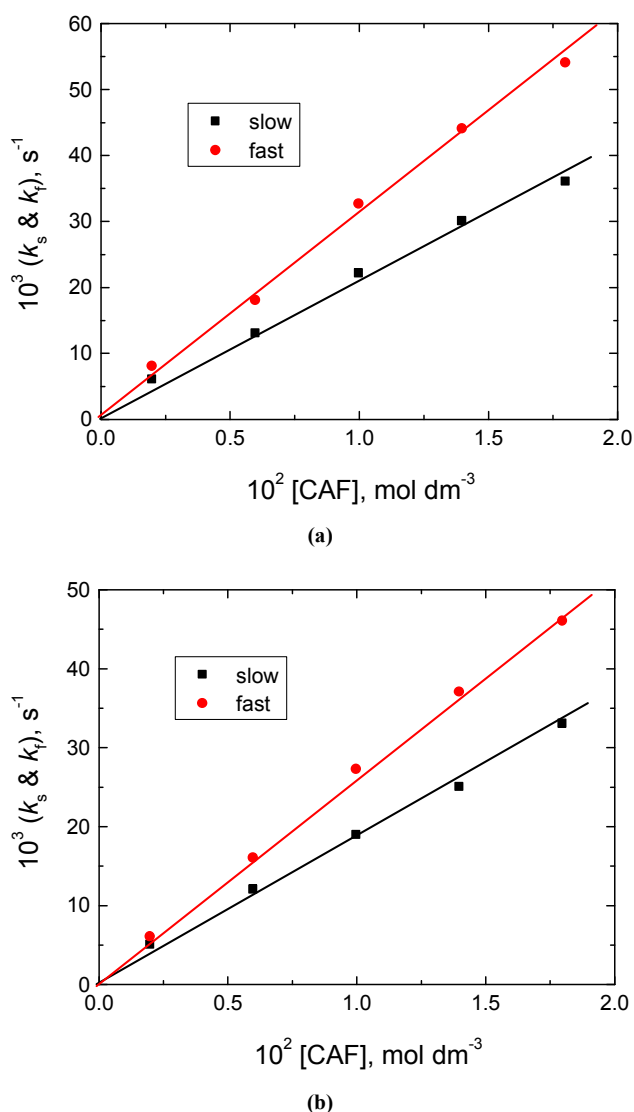


Figure 3. Plots of the pseudo-first order rate constants (k_s and k_f) versus [CAF] in the oxidations of caffeine by permanganate ion in: (a) perchloric and, (b) sulfuric acid solutions. $[\text{MnO}_4^-] = 4.0 \times 10^{-4}$, $[\text{H}^+] = 0.5$ and $I = 1.0$

mol dm^{-3} at 25°C .

3.6. Rate Dependence on Acids Concentration

The influence of both perchloric and sulfuric acid on the rates was investigated by varying the hydrogen ion concentration in the range: $0.1 - 0.9 \text{ mol dm}^{-3}$, keeping all other reactants concentrations constant. Plots of $\log k_s$ and $\log k_f$ versus $\log [\text{H}^+]$ were also linear with slopes ranging between 0.84 and 0.78 in both acids, Figure 4, suggesting that the orders of reactions with respect to [acid] were less than unity.

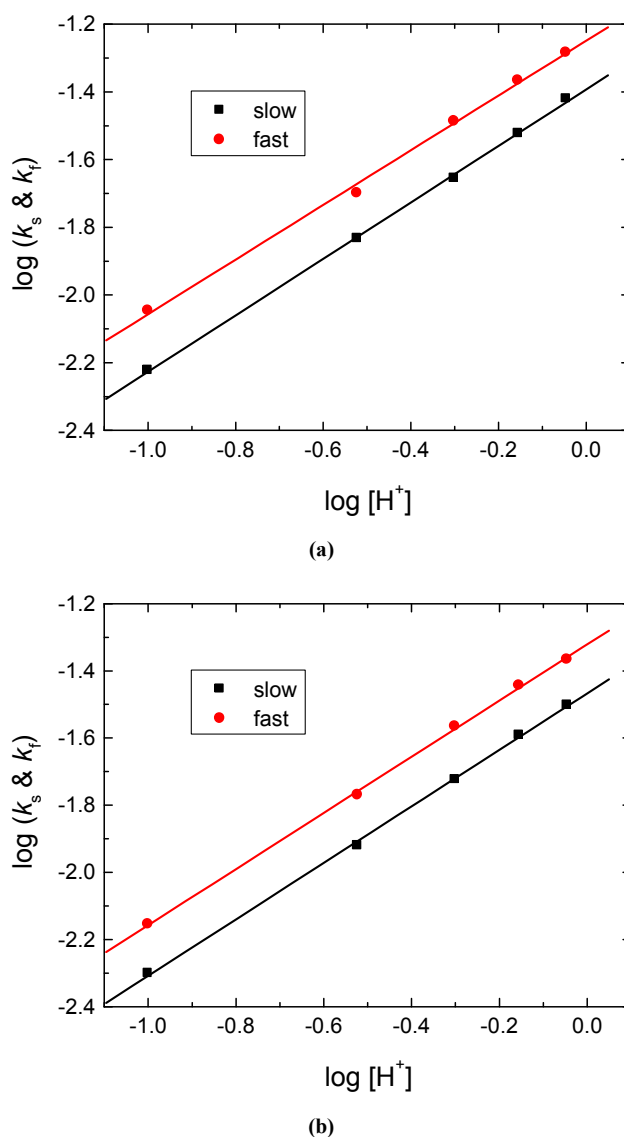


Figure 4. Plots of $\log k_s$ and $\log k_f$ versus $\log [\text{H}^+]$ in the oxidations of caffeine by permanganate ion in: (a) perchloric and, (b) sulfuric acid solutions. $[\text{MnO}_4^-] = 4.0 \times 10^{-4}$, $[\text{CAF}] = 0.01$ and $I = 1.0 \text{ mol dm}^{-3}$ at 25°C .

3.7. Effect of Ionic Strength and Dielectric Constant

The ionic strength effect was studied by varying the concentration of NaClO_4 in the reactions media at constant concentrations of permanganate, caffeine and acid. It was

found that variation in ionic strength did not affect the rates as observed from the data listed in Table 1.

The effect dielectric constant (D) was also studied by varying the acetic acid - water content in the reaction mixture with all other conditions being kept constant. The data clearly revealed that the rate constants did not significantly affected by the decrease in dielectric constant of the solvent mixture; i.e. increase in acetic acid content.

3.8. Rate Dependence on Initially Added Manganese(II) Product

The initially added product, Mn(II), was studied in the concentration range of $(1.0 - 9.0) \times 10^{-4} \text{ mol dm}^{-3}$, while keeping the reactant concentrations and all other conditions constant. As the Mn(II) concentration increases the reaction rate also increases with a sigmoid profile for the reaction-time curves were obtained, indicating autocatalytic activity of Mn(II). The orders with respect to $[\text{Mn(II)}]$ were less than unity, as shown in Figure 5(a).

3.9. Rate Dependence on Added Fluoride Ions

The influence added F^- ions was examined by addition of its salt to the reaction medium in the concentration range of $(1.0 - 9.0) \times 10^{-4} \text{ mol dm}^{-3}$, while keeping all other conditions constant. The experimental results indicated that the reaction rate was found to decrease upon addition of F^- ions as shown in Figure 5(b).

3.10. Effect of Temperature

The rates of the reactions were carried out at four different temperatures between 288 and 318 K at constant concentrations of the reactants and other conditions being constant. The results indicate that the rate constants increased with rise in temperature. The activation parameters of the second order rate constant (k_2) are calculated using Eyring and Arrhenius plots and are listed in Table 2.

3.11. Polymerization Study

To check the existence of free radicals in the reactions under investigations, the reactions mixtures were mixed with identified quantities of acrylonitrile monomer and kept for 6 hours in an inert atmosphere. On diluting the reactions mixtures with methanol, heavy white precipitates of

polymers were formed, indicating the intervention of free radicals in the present reactions. Blank experiments with either caffeine or permanganate alone with acrylonitrile did not induce any polymerization under the same condition as those induced for the reaction mixture.

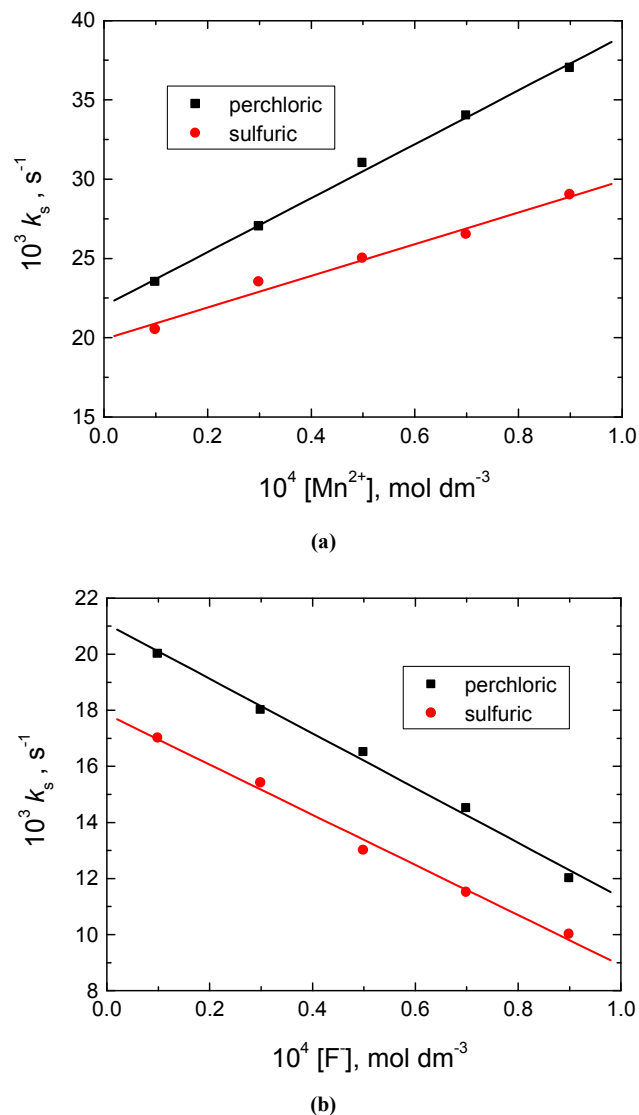


Figure 5. Effect of added: (a) manganese(II) and, (b) fluoride ions on the pseudo-first order rate constant in the oxidations of caffeine by permanganate ion in perchloric and sulfuric acids solutions. $[\text{MnO}_4^-] = 4.0 \times 10^{-4}$, $[\text{CAF}] = 0.01$ and $I = 1.0 \text{ mol dm}^{-3}$ at 25°C .

Table 2. Activation parameters of the second order rate constant (k_2) in the oxidations of caffeine by permanganate ion in perchloric and sulfuric acids solutions. $[\text{MnO}_4^-] = 4.0 \times 10^{-4}$, $[\text{CAF}] = 0.01$, $[\text{F}^-] = 0.5$ and $I = 1.0 \text{ mol dm}^{-3}$.

| Acid | $\Delta S^\ddagger, \text{J mol}^{-1}\text{K}^{-1}$ | $\Delta H^\ddagger, \text{kJ mol}^{-1}$ | $\Delta G^\ddagger_{298}, \text{kJ mol}^{-1}$ | $E_a^\ddagger, \text{kJ mol}^{-1}$ |
|------------|---|---|---|------------------------------------|
| Perchloric | 81.60 | 63.12 | 38.80 | 65.07 |
| Sulfuric | 67.33 | 65.71 | 45.64 | 68.89 |

4. Discussion

Spectral changes in both perchloric and sulfuric acid solutions, illustrated in Figure 1(a, b), show gradual disappearance of permanganate ion at its absorption

maximum as the reactions proceed suggesting reduction of permanganate ion by caffeine substrate. It can be also observed that there are no rise and fall in the absorption spectra above $\lambda = 600 \text{ nm}$ which may be considered as an evidence against complex formation between oxidant and substrate. A further evidence against complex formation was

the Michaelis-Menten [33] plots of $1/k_s$ against $1/[CAF]$ which gave straight lines passing through the origin (Figure 6). Similar behavior was reported elsewhere [34, 35].

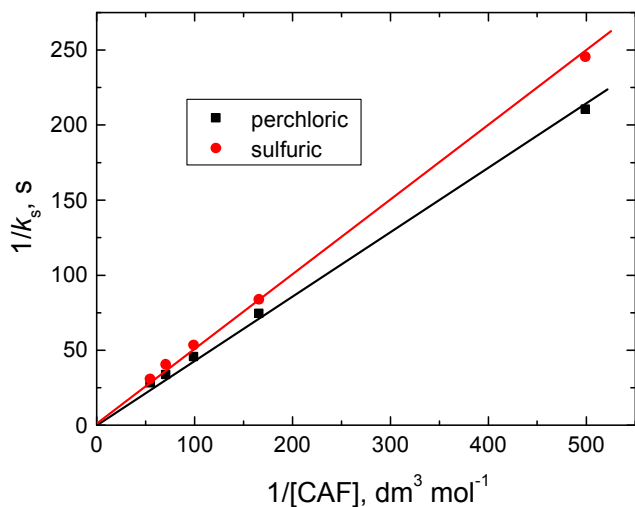
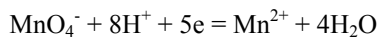
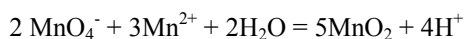


Figure 6. Plots of $1/k_s$ versus $1/[CAF]$ the oxidation of caffeine by permanganate ion in perchloric acids medium. $[CAF] = 0.01$, $[MnO_4^-] = 4.0 \times 10^{-4}$, $[H^+] = 0.5$, and $I = 1.0 \text{ mol dm}^{-3}$ at 25°C .

In general, reduction of permanganate in acid medium goes to either Mn(II) or Mn(IV), where the reduction potential of the Mn(VII)/Mn(II) couple is 1.51 V and of the Mn(VII)/Mn(IV) couple is 1.695 V [36] according to the following equations:



and in the presence of an excess of permanganate ion, the product is MnO_2 :



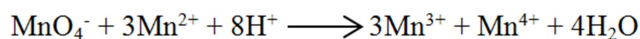
Manganese(VII) (MnO_4^-) is reduced to Mn(II) during oxidation processes via many manganese intermediate species having different oxidation states such as Mn(VI), Mn(V), Mn(IV) and Mn(III). On the other hand, Mn(II), the ultimate reaction product, acts as an autocatalyst. The appearance of these intermediate oxidation states depends upon various reaction conditions, types of substrate and their stability. The manganese chemistry involved in these multistep redox reactions is an important source of information because the manganese intermediates are relatively easy to identify when they have a sufficiently long lifetimes, and the oxidation states of the intermediate species permit useful conclusions about possible reaction mechanisms, including the nature of the intermediates [15].

During the oxidation by permanganate ion in acid media, the intermediate Mn(IV) species may be formed which could be H_2MnO_4 , H_2MnO_3 or a water-soluble colloidal MnO_2 [15]. The MnO_2 is unstable due to its reaction with acid producing Mn(II). The appearance of a new band at a wavelength of 418 nm suggests intervention of Mn(IV) [37, 38] as a reduced product of the oxidant. Also, Mn(IV) formation may be due to the reaction between Mn(V) and

Mn(III).

The sigmoid profile, observed in the reaction-time curves gives a conclusive evidence for an autocatalytic oxidation process in acidic medium in which Mn(II) species are responsible for this effect. As the reactions are of catalytic nature, they obey the rate expression: $(A_t - A_\infty) = B_0 e^{-k_s t} + P_0 e^{-k_f t}$ [39] where k_s and k_f are the first order rate constants for the slow (induction) and fast (auto-acceleration) periods, A_t and A_∞ are the absorbance at times t and infinity; while B_0 and P_0 represent the absorbance change for the slow and fast reacting species, respectively. The rate constants were obtained by drawing a straight line through the slow-time linear portion (k_s) of the first order plot and extrapolating the time back to zero time (B_0). The rate of oxidation for the auto-acceleration period, k_f , was obtained from plots of $\ln[(A_t - A_\infty) - (A_\infty - A_t)]$ versus t where the quantity $(A_t - A_\infty)$ represents the experimental point and $(A_\infty - A_t)$ is the extrapolated one at time t . Similar redox reactions involving permanganate as an oxidant, which followed the same behavior, were reported elsewhere [40, 41].

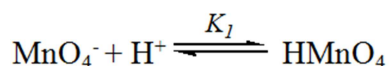
Since Mn^{2+} is one of the oxidation products of permanganate ion in acid media, its effect on the reaction rate should be examined. It is well known [42] that acidified permanganate is reduced by addition of Mn^{2+} to give Mn^{3+} and Mn^{4+} according to the following equation



where Mn^{3+} and Mn^{4+} can be removed by fluoride ions owing to the formation of stable complexes with these ions [40]. If MnO_4^- ion is primarily responsible for oxidation, a reduction in the initial rate should be observed in the presence of Mn^{2+} ions which reduce the concentration of permanganate ions [43]. If the intermediates Mn^{3+} and/or Mn^{4+} are the reactive oxidizing species, addition of Mn^{2+} should accelerate the reaction rate. Similarly, addition of F^- ions should retard the rate of reaction if the intermediate manganese(III) and/or manganese(IV) ions are the mainly responsible for the oxidation and cause no significant change if MnO_4^- ions are the principle oxidizing entities. Furthermore, the catalytic effect of Mn^{2+} may be attributed to the formation of a complex with the substrate which is then oxidized by $HMnO_4$.

The obtained results showed a notable increase in the reaction rate upon initial addition of Mn(II) ion to the reaction medium as illustrated in Figure 5(a). Also, further increase in initial Mn(II) concentration and maintaining the Mn(II) concentration equal to the permanganate ion concentration led to a complete disappearance of the sigmoid form. The complete disappearance of the sigmoid form as well as the decrease in the reaction rate upon the addition of fluoride ion, Figure 5(b), may suggest that Mn(III) and/or Mn(IV) are the principle reactive species in the fast final period.

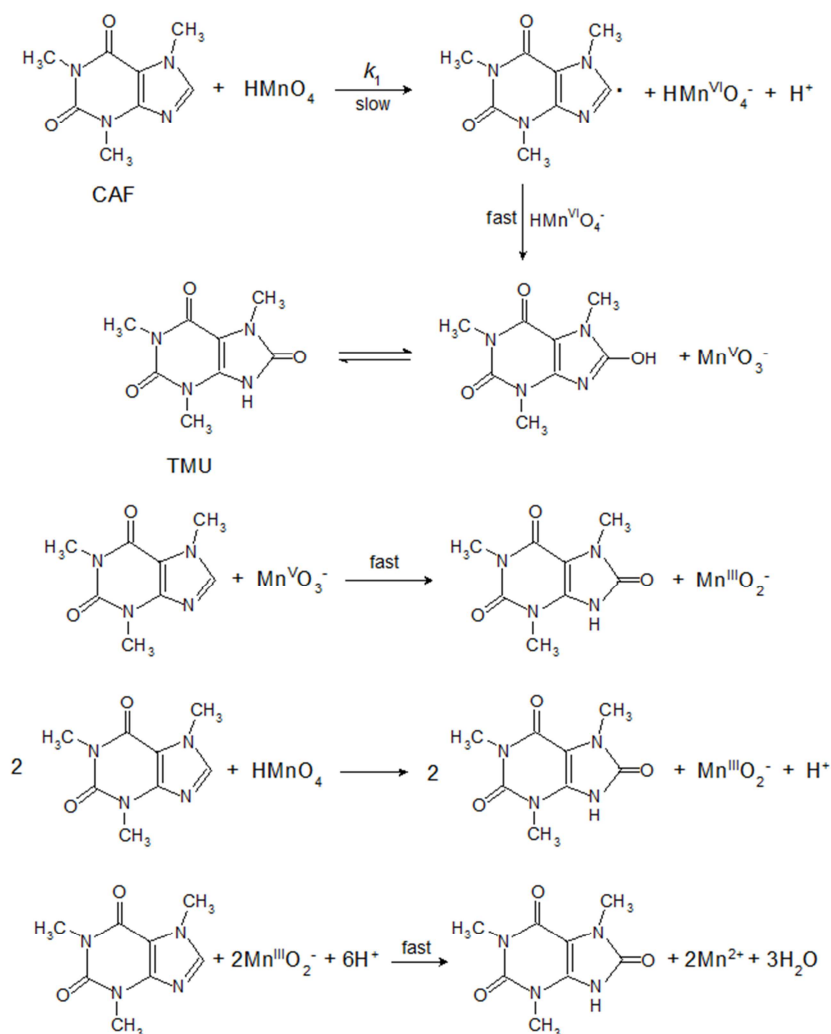
Many investigators [34, 35, 44-46] have suggested that permanganate ion in acid media tends to protonate to form a more powerful species, namely permanganic acid according to the following equilibrium:



where K_1 is the protonation constant of permanganate ion. The protonation of permanganate ion shifts the $\text{Mn}^{\text{VII}}/\text{Mn}^{\text{VI}}$ couple to a more positive value (+1.3 V), which makes HMnO_4 a stronger oxidizing agent than MnO_4^- . The observed enhancement of the reactions rates with increasing hydrogen ion concentrations supports this suggestion.

The present reactions between permanganate ion and caffeine in both perchloric and sulfuric acid solutions have 2:5 stoichiometry (MnO_4^- : CAF), with first order dependences on both substrate and oxidant and an apparent less than unity order with respect to the acids concentrations. In view of the above arguments, the reactions mechanism for which all the observed orders in each constituent, such as [oxidant], [reductant] and $[\text{H}^+]$, are well accommodated is suggested and illustrated in Scheme 1. The mechanism involves attack of the powerful oxidant, acid permanganate, on the first mole of caffeine substrate in the rate determining step to give a free radical derived from caffeine and an intermediate $\text{Mn}(\text{VI})$ species. The observed insignificant effect of either ionic strength or dielectric constant of the medium on the

reactions rates implies association of two neutral molecule [47, 48], i.e. between caffeine and acid permanganate. Then, the intermediate $\text{Mn}(\text{VI})$ reacts with a free radical, producing 8-hydroxy caffeine which tautomerises to the final oxidation product of caffeine, 1,3,7-trimethyluric acid (TMU). In a further fast step the intermediate $\text{Mn}(\text{V})$, being very active and unstable in acid medium, reacts with another mole of caffeine to form again TMU product and an intermediate $\text{Mn}(\text{III})$ species. Similar to the previous two steps, other two moles of caffeine substrate react with acid permanganate species to form again two moles of TMU product and $\text{Mn}(\text{III})$ species. The last step is the rapid attack of the two formed $\text{Mn}(\text{III})$ intermediate species on another caffeine mole of caffeine to give the last TMU product and the final oxidation product of permanganate, $\text{Mn}(\text{II})$, satisfying the obtained stoichiometry. The failure of spectroscopic detection of the proposed intermediate $\text{Mn}(\text{V})$ and $\text{Mn}(\text{III})$ species as the reaction proceeded may be interpreted by its extreme short lifetime which undergoes a rapid disproportionation or due to the low concentrations of $\text{Mn}(\text{V})$ and $\text{Mn}(\text{III})$ intermediates obtained under our experimental conditions. However, there are reports in the literature for the existence of $\text{Mn}(\text{V})$ and $\text{Mn}(\text{III})$ [46].



Scheme 1. Mechanism of oxidation of caffeine by permanganate ion in acid media.

According to the proposed mechanistic Scheme 1, the oxidation rate can be expressed by the following rate law:

$$\text{Rate} = \frac{-d[\text{MnO}_4^-]}{dt} = k_1[\text{CAF}][\text{HMnO}_4] \quad (1)$$

$$K_1 = \frac{[\text{HMnO}_4]}{[\text{MnO}_4^-][\text{H}^+]}, [\text{HMnO}_4] = K_1[\text{MnO}_4^-][\text{H}^+] \quad (2)$$

Substituting Eq. (2) into Eq. (1) leads to:

$$\text{Rate} = k_1 K_1 [\text{CAF}][\text{MnO}_4^-][\text{H}^+] \quad (3)$$

The total concentration of MnO_4^- is given by:

$$[\text{MnO}_4^-]_T = [\text{MnO}_4^-]_F + [\text{HMnO}_4] \quad (4)$$

where 'T' and 'F' stand for total and free concentrations.

Therefore,

$$[\text{MnO}_4^-]_T = [\text{MnO}_4^-]_F + K_1[\text{MnO}_4^-]_F[\text{H}^+] \quad (5)$$

$$[\text{MnO}_4^-]_F = \frac{[\text{MnO}_4^-]_T}{1 + K_1[\text{H}^+]} \quad (6)$$

Substituting Eqs. (6) into Eq. (3) (and omitting 'T' and 'F' subscripts) leads to:

$$\text{Rate} = \frac{k_1 K_1 [\text{MnO}_4^-][\text{CAF}][\text{H}^+]}{1 + K_1[\text{H}^+]} \quad (7)$$

Under pseudo-first order condition, the rate-law can be expressed by equation (8):

$$\text{Rate} = \frac{-d[\text{MnO}_4^-]}{dt} = k_s[\text{MnO}_4^-] \quad (8)$$

Comparing Eqs. (7) and (8), we get the following relationship:

$$k_s = \frac{k_1 K_1 [\text{CAF}][\text{H}^+]}{1 + K_1[\text{H}^+]} \quad (9)$$

With rearrangement of Eq. (9), the following equation is obtained:

$$\frac{[\text{CAF}]}{k_s} = \frac{1}{k_1 K_1 [\text{H}^+]} + \frac{1}{k_1} \quad (10)$$

According to Eq. (10), other conditions being constant, a plot of $[\text{CAF}]/k_s$ versus $1/[\text{H}^+]$ is expected to be linear and is found to be so (Figure 7). The slope and intercept of this plot yield values of K_1 and k_1 at 25°C. This value of K_1 is in agreement with the literature [35, 49].

The activation parameters listed in Table 2 may be interpreted as follows. The obtained positive values of ΔS^\ddagger suggest that the reactions point towards the outer-sphere pathway [50]. The positive values of both ΔH^\ddagger and ΔG^\ddagger confirm endothermic formation of the intermediate

complexes and their non-spontaneities, respectively.

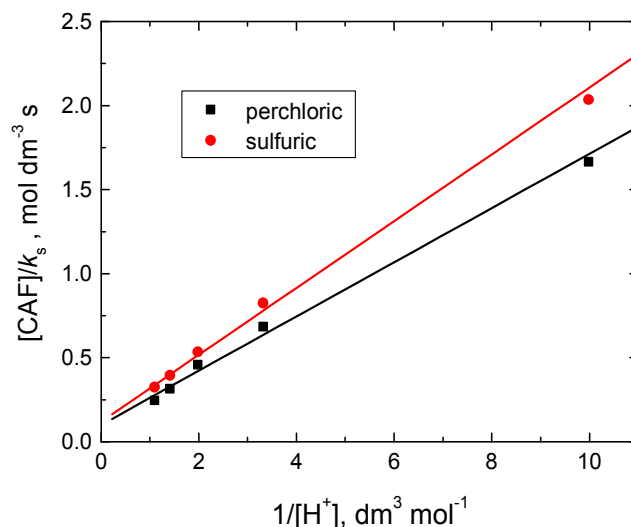


Figure 7. Verification of equation (5) for the oxidations of caffeine by permanganate ion in perchloric and sulfuric acids solutions. $[\text{MnO}_4^-] = 4.0 \times 10^{-4}$ and $I = 1.0 \text{ mol dm}^{-3}$ at 25°C.

Table 3. Values of k_1 and K_1 in the oxidations of caffeine by permanganate ion in perchloric and sulfuric acids solutions at 25°C.

| Acid | $k_1, \text{dm}^3 \text{mol}^{-1} \text{s}^{-1}$ | $K_1, \text{dm}^3 \text{mol}^{-1}$ |
|------------|--|------------------------------------|
| Perchloric | 9.7 | 0.53 |
| Sulfuric | 9.1 | 0.51 |

5. Conclusions

The kinetics of oxidations of caffeine by permanganate ion in both perchloric and sulfuric acids solutions has been studied. The main oxidation product of caffeine was identified in both cases as 1,3,7-trimethyluric acid. Under comparable experimental conditions, the oxidation rate in perchloric acid was slightly higher than that in sulfuric acid. The reactions constants involved in the different steps of the oxidations mechanism along with the activation parameters have been evaluated and discussed.

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