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RESEARCH ARTICLE **PHYSICO-CHEMISTRY**

Effect of Heat on the Stability and Degradation of Vitamin C: A Thermodynamic and Kinetic Study

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ABSTRACT

Vitamin C is an important antioxidant used extensively in pharmaceutical, food and cosmetic industries for its vital biological functions. But it is extremely prone to heat, light and oxygen–resulting in quick degradation and loss of efficacy throughout processing and storage. In this study, the thermal degradation, kinetic and thermodynamic stability analysis of vitamin C at different temperature in aqueous solutions were evaluated by UV–VIS spectrophotometry. The feasibility was investigated for vitamin C solutions at concentrations of 0.8% and 0.6% (w/v), with temperatures from 25 to 45 °C, over a time span of 5 to 25 minutes. The λmax was at 285 nm, with a decreasing absorbance as the temperature and exposure time increased indicated an increment of thermal degradation. The degradation process was characterized by first-order kinetic at all temperatures studied. According to results, the activation energy values were determined as 84.35 and 94.05 kJ mol^{-1} for solutions of 0.8% and 0.6%, respectively, which highlighted a strong temperature effect on the degradation rate. Thermodynamic parameters showed positive values for enthalpy and entropy, suggesting that the degradation process is endothermic ($\Delta H > 0$) and favors disorder in their molecular surroundings. Moreover, Gibbs free energy decreased with increasing temperature that the degradation process was increasingly spontaneous at higher temperatures. Overall, the findings offer useful practical insights towards optimizing storage conditions, improving thermal processing methods and possibly designing packaging systems to enhance stability and shelf life of products containing vitamin C for industrial purposes.

التأثير الحراري على استقراروتحلل فيتامين C: دراسة ديناميكية حرارية وحركية

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الكلمات المفتاحية:

فيتامين C
مطياف ضوئي
الامتصاص
الديناميكا الحرارية
رتبة التفاعل
الحرارة

الملخص

يُعدّ فيتامين "C" مضادًا للأكسدة هامًا يُستخدم على نطاق واسع في الصناعات الدوائية والغذائية والتجميلية لوظائفه البيولوجية الحيوية. إلا أنه شديد الحساسية للحرارة والضوء والأكسجين، مما يؤدي إلى تحلله السريع وفقدان فعاليته أثناء عمليات التصنيع والتخزين. في هذه الدراسة، تم تقييم التحلل الحراري والحركية والاستقرار الديناميكي الحراري لفيتامين "C" عند درجات حرارة مختلفة في محاليل مائية باستخدام مطيافية الأشعة فوق البنفسجية والمرئية. دُرست جدوى استخدام محاليل فيتامين C"بتركيز 0.8% و0.6% (وزن/حجم)، عند درجات حرارة تتراوح بين 25 و45 درجة مئوية لمدة تتراوح بين 5 و25 دقيقة. كان الطول الموجي الأقصى عند 285 نانومتر، مع انخفاض الامتصاص مع ارتفاع درجة الحرارة وزيادة مدة التعرض، مما يشير إلى زيادة التحلل الحراري. اتسمت عملية التحلل بحركية من الدرجة الأولى عند جميع درجات الحرارة المدروسة. أظهرت النتائج أن قيم طاقة التنشيط بلغت 84.35 و94.05 كيلوجول/مول لمحاليل بتركيز 0.8% و0.6% على التوالي، مما يُبرز تأثير درجة الحرارة الكبير على معدل التحلل. وأظهرت المعاملات الديناميكية الحرارية قيمًا موجبة لكل من المحتوى الحراري والإنتروبيا، مما يشير إلى أن عملية التحلل ماصة للحرارة ($\Delta H > 0$) وتُفضّل عدم الانتظام في البيئة الجزيئية المحيطة. علاوة على ذلك، انخفضت طاقة جيبس الحرة مع ارتفاع درجة الحرارة، مما يعني أن عملية التحلل أصبحت أكثر تلقائية عند درجات الحرارة المرتفعة. وبشكل عام، تُقدّم هذه النتائج رؤى عملية مفيدة لتحسين ظروف التخزين، وتطوير أساليب المعالجة الحرارية، وربما تصميم أنظمة تغليف لتعزيز استقرار ومدة صلاحية المنتجات التي تحتوي على فيتامين "C" للأغراض الصناعية.

Introduction

Vitamin C or, L-ascorbic acid was noted as the vital nutrient for the treatment of scurvy (and a version from this word, scorbutus, a-scorbutus). Prior to the onset of an identifiable nomenclature, humans used "fat soluble vitamin A" and "water soluble vitamin B." Usually, vitamin C means L-ascorbic acid, but other times it can refer to L-dehyroascorbic acid (which is easily converted to L-ascorbic acid in the body), as shown in Figure (1). Legally and in the academic field, vitamin C is a naturally occurring, somewhat acidic, water-soluble compound that can be found in many plants [1]. In fact, over 100 types of plants worldwide contain vitamin C in their leaves, fruits, or roots. Among those plants, some of the highest conce ntrations contain citrus (*Citrus*

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spp.), strawberries (*Fragaria* × *ananassa*), kiwifruit (Actinidia deliciosa), guava (*Psidium guajava*), and sea grape (Malpighia emarginata). Black currants (*Ribes nigrum*), papaya (*Carica papaya*), and sweet bell pepper (*Capsicum annuum*) are also rich sources of vitamin C. Rose hips (Rosa canina), amla (*Phyllanthus emblica*), kakadu plum (*Terminalia ferdinandiana*), and camu (*Myrciaria dubia*) also provide significant amounts of vitamin C. Even parsely (*Petroselinum crispum*), a greener than other herbs, contains vitamin C [2, 3].

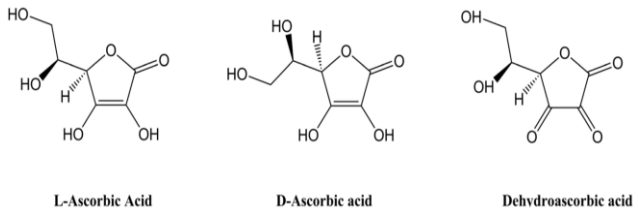


Figure 1: Vitamin C, in its reduced form (ascorbic acid), and oxidized form (dehydroascorbic acid)

Chemically, vitamin C is a carbon and oxygen-containing molecule consisting of a six-membered lactone ring with hydroxyl group and enediol functional group. The molecule has a systematic IUPAC name of (5R)-[(1S)-1,2-dihydroxyethyl]-3,4-dihydroxy furan-2(5H)-one, which accurately describes the structure of the molecule. The configuration of the furanone ring (furan-2(5H)-one) shows hydroxyl groups at the positions 3 and 4 (R configuration), while the side chain (1,2-dihydroxyethyl) has an (S configuration) group. Many functional groups are represented in the molecules chemical structure which comprises hydroxyl (–OH), enediol and lactone to mention a few. The molecular formula of vitamin C is $C_6H_8O_6$ with a molar mass of 176.12 g/mol [4, 5] Vitamin C can be produced by plants and some animals, ingesting foods from plant origins is the only method by which humans obtain Vitamin C. Because of the enediol group, vitamin C is an excellent reducing agent and the enediol group allows Vitamin C to be an antioxidant. It is very soluble in water due to its hydroxyl groups, allowing it to act as a cofactor in so many enzyme-catalyzed reactions in addition to being insoluble in chloroform, ether and benzene. It will form a clear colorless to slightly yellow solution. Vitamin C is an acid with a pKa of around 4.2 and will be mostly ionized at physiological pH, which contributes to its solubility in aqueous mixtures. It is able to form hydrogen bonds, which facilitate its interaction with many biomolecules including enzymes and collagen, which are necessary for its function in tissue repair and immune responses. This molecule also plays a role in the reduction of metal ions and it functions as an antioxidant to provide cytoprotection from oxidative stress [6, 7]. Vitamin C appears as a crystalline powder that is white to pale yellow with an aqueous solution that has a pH range of 2.2 to 2.5 at a concentration of five percent. Vitamin C has a CAS registration number of 50-81-7, a density of 1.65 g/cm³, and a melting point of 190-192 ℃. It has a high boiling point of 553 ℃. It has good solubility in water of 330 g/100 L. additionally; vitamin C has a very low vapor pressure of 0.001 mmHg [8].

Pharmacologically, as previously mentioned, vitamin C is an effective antioxidant and serves as an essential cofactor for many enzymatic reactions in humans. Vitamin C serves several functions, including collagen synthesis, immune function, and protection against cell oxidative stress by neutralizing free radicals. Vitamin C also improves the absorption of non-heme iron from plant-based foods and regenerate other antioxidants, such as vitamin E. Vitamin C, unlike vitamin E, is water soluble and stored in relatively small amounts. Therefore, dietary intake is needed regularly to maintain sufficient levels. At low to moderate doses (up to 200 mg), around 70-90% of vitamin C is well absorbed in the small intestine, but absorption plummets at higher doses due to saturation of transporters [9, 10]. The vitamin is distributed throughout the body, with the greatest concentrations in the adrenal glands, the pituitary gland, and leukocytes. When vitamin C is present at normal levels, its plasma half-life is between 10 and 20 days; however, when plasma levels are at high concentrations, its half-life is typically only a few hours. Large excess amounts of vitamin C are eliminated by the kidneys as either ascorbic acid or metabolites of ascorbic acid such as oxalate. In high amounts, vitamin C can cause gastrointestinal disturbances like diarrhea. Oral administration of ascorbic acid (1.25g) can boost plasma ascorbic acid to 134.8 ± 20.6 (μmol/L). In addition to eating naturally occurring vitamin C sources like fruits and vegetables, there is a growing consumer interest in vitamin C-fortified dietary supplements and foods in order to maintain the needed concentration of ascorbic acid in the body. Vitamin C is necessary for normal physiological functions in the body and is particularly important for the synthesis and metabolism of tyrosine, folic acid, and tryptophan, and also notably for the hydroxylation of glycine, proline, lysine, carnitine, and catecholamines. Further, it also plays a supporting role in converting cholesterol to bile acids to lower blood cholesterol levels [11, 12]. There have been numerous investigations into how temperature affects the breakdown of vitamin C and its degradation follows first-order kinetics, meaning that it decreases at a constant rate dependent upon time and is quite sensitive to temperature. Increasing the temperature means greater degrees of both oxidation and decomposition occur quickly, thus resulting in the loss of significant amounts of vitamin C. For example, in [13] the authors reviewed ascorbic acid (AA) and dehydroascorbic acid (DHA) degradation kinetics in different oxygen concentrations from 50℃ to 90℃, concluding that as temperature increased, so did the rate of degradation with first order kinetics. Similarly, [14] assessed vitamin C degradation in arboreal tomato juice from 70℃, 80℃ and 90℃ finding that degradation increased with increasing temperature with first order kinetics. The activation energy associated with degradation was reported as 41.27 kJ mol-1 which further confirms that temperature was the major factor that affected degradation. In addition, [15] investigated the effect of both relative humidity and temperature on the stability of powdered vitamin C and found that as temperature increased, there was an increase in both degradation and loss of shelf-life/stability. Moreover, [16] studied the thermal degradation kinetics of vitamin C in marula, mango and guava pulp at temperatures of 80-150 ℃. They reported that the degradation of vitamin C increased significantly as temperature increased, and that degradation at high temperature may not only follow simple first-order kinetics but may also display biphasic characteristics. Additionally, [16] studied the thermal degradation of vitamin C using TGA and DTA techniques, estimating kinetic parameters such as activation energy and pre-exponential factors, and concluded that the degradation of vitamin C can be described by an n-th order kinetic model with an activation energy of approximately 139.55 kJ mol^{-1}.

This study is important because it explains how temperature affects the stability and degradation of vitamin C over time. Kinetic analysis helps determine the speed at which vitamin

C degrades under different temperatures, while thermodynamic analysis explains the energy changes associated with the degradation process and the stability of vitamin C under thermal conditions. Understanding these relationships can help improve storage and processing conditions, reduce vitamin C loss, and maintain the nutritional quality of food and pharmaceutical products.

Generally, the main objective of this study was to investigate the effect of temperature on the thermal degradation and stability of vitamin C in aqueous solutions. Kinetic analysis was used to determine the degradation rate and reaction order, while thermodynamic analysis was applied to evaluate the energetic behavior of the degradation process, including activation energy, enthalpy, entropy, and Gibbs free energy. Therefore, the relation between vitamin C and thermodynamic/kinetic analysis is based on studying how temperature influences its degradation behavior and stability.

Material and Methods

Chemicals and Reagents

All chemicals, reagents and solvents utilized were of analytical grade, used as received without further purification, and sourced from Scharlau and Sigma-Aldrich.

Instrument and Equipment

UV/VIS spectrophotometer (DU 800, BECKMAN COULTER) was used to quantify vitamin C at different concentrations using a 1 cm quartz cuvette. Additional equipment included an analytical balance, heater, grinder, glassware, and standard laboratory tools for sample preparation and measurement.

Preparation of Stock Solutions and Experimental Conditions

A 2% vitamin C stock solution was prepared and diluted to 0.2–0.8% concentrations. UV–VIS analysis was used to determine λmax, and the highest concentration was selected for further study. Measurements were conducted at 25–45 °C to represent typical storage and processing conditions, and at 5–25 min intervals to evaluate the short-term effect of temperature on vitamin C stability over time.

Wavelength Selection and Measurements

In the UV-Visible spectrum, vitamin C has its λ_{max} at 285nm, which gives it the highest absorbance at that wavelength. Therefore, that wavelength was used for each assay to achieve maximum accuracy and sensitivity. A stock solution of 2% (*w/v*) was used to prepare the calibration. The stock solution was diluted to three concentrations (0.2, 0.5, and 0.8%, w/v). Two of those concentrations were incubated at temperatures ranging from 30-45℃ for 5-25 minutes. After the incubation, absorbance was measured for each sample to determine the effect of temperature and time on the stability of vitamin C.

Thermodynamic and Kinetic Parameters Calculation

The graphical analysis was used to derive both the thermodynamic and kinetic constant from the experimental data and then run through the following programs to derive the data: using Microsoft Excel and Origin to find reaction order, half-life, and slope. The Arrhenius plot will be used to determine both the activation energy and the thermodynamic constants. The temperature dependence of the vitamin C degradation kinetics was evaluated; Figure 2 below shows the graphical analysis that was performed to derive the kinetic and thermodynamic constants for vitamin C degradation.

Thermodynamic Parameters Calculation:

Along with the kinetic analysis, various thermodynamic parameters were calculated to provide a thermodynamic characterization of the thermal degradation of vitamin C. The temperature coefficient (Q_{10}) was determined from [18],

$$Q_{10} = \left(\frac{k_2}{k_1}\right)^{\frac{10}{T_2 - T_1}} \quad (1)$$

The Gibbs free energy (ΔG) was calculated using the Gibbs–

$$\Delta G = \Delta H - T.\Delta S \quad (2)$$

Helmholtz equation [19]:

The enthalpy of activation (ΔH‡) was estimated from the

$$\Delta H‡ = E_a - RT \quad (3)$$

Arrhenius-derived activation energy (E_a) as [20]:

The activate activation entropy (ΔS‡) was determined from the y-intercept of the linear form of the Eyring equation.[21]

$$\ln\left(\frac{k}{T}\right) = \ln\left(\frac{kB}{T}\right) + \frac{\Delta S‡}{R} - \frac{\Delta H‡}{R} - \left(\frac{1}{T}\right) \quad (4)$$

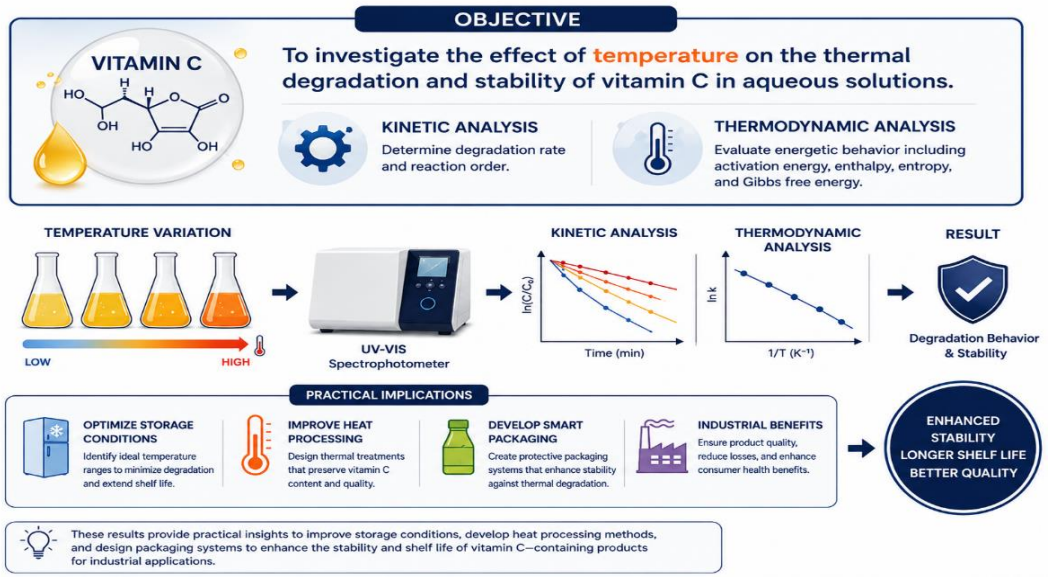


Figure 2: Diagrammatic display of the steps of the study objectives

Where, k_1 and k_2 are the reaction rate constants at temperatures T_1 and T_2, respectively, T is the absolute temperature in Kelvin (K), and Q_{10} is the temperature coefficient. ΔG, ΔH, and ΔS represent Gibbs free energy, enthalpy, and entropy changes, respectively, while ΔH‡ and ΔS‡ denote the activation enthalpy and activation entropy. E_a is the activation energy, R is the universal gas constant (8.314 $J \cdot mol^{-1} \cdot K^{-1}$), k is the reaction rate constant, kB is Boltzmann's constant (1.38×10^{-23} $J \cdot K^{-1}$), and h is Planck's constant (6.626×10^{-34} J·s). [22,23]

$$E_T = (hC\,N_A) / \lambda \quad (5)$$

$$\Delta G‡ = -RT\, ln\, (kh / k_B\, T) \quad (6)$$

And the equilibrium constant (Keq) determined from: [24]

$$K_{eq} = e^{-\Delta G / RT} \quad (7)$$

Where, E_T represents the electronic transition energy, h is Planck's constant (6.626×10^{-34} J·s), c is the speed of light (3.0×10^8 $m \cdot s^{-1}$), N_A is Avogadro's number (6.022×10^{23} mol^{-1}), and λ is the wavelength (m) obtained from UV–VIS absorption data. ΔG‡ is the Gibbs free energy of activation ($J \cdot mol^{-1}$), R is the universal gas constant (8.314 $J \cdot mol^{-1} \cdot K^{-1}$), T is the absolute temperature in Kelvin, k is the rate constant, kB is Boltzmann's constant (1.38×10^{-23} $J \cdot K^{-1}$), and h is Planck's constant. K_{eq} is the equilibrium constant, and ΔG is the Gibbs free energy change ($J \cdot mol^{-1}$).

All thermodynamic parameters were calculated based on Arrhenius and Eyring plot to describe the energetic nature of the degradation reaction and its thermal dependence.

Kinetic Parameter Calculation:

Vitamin C degradation was assumed to first order reaction kinetics. Thus, the rate constant (*k*) was determined from[25]:

$$k = (2.303/t)\, (\log C_0 / C_t) \quad (8)$$

Where, *k* is the first order rate constant (min^{-1}), C_o is the initial vitamin C concentration, C_t is concentration at time t and t is time (min). The half-life of the reaction was retrieved from: The half-life of the reaction was determined from the relationship[26]:

$$t_{½} = 0.693/k \quad (9)$$

The activation energy (Ea) was determined based on the Arrhenius relationship from[27]:

$$Ea = -(Slope) \times R \quad (10)$$

Finally, the pre-exponential factor (A) was determined as [28]:

$$A = k\, e^{Ea / RT} \quad (11)$$

Statistical analysis

To assess the validity of the findings, statistical analysis was used. Data are presented in terms of mean ± standard deviation (SD), standard error (SE), and coefficient of variation (CV). Linear regression analysis was used to assess the correlation of two variables. Goodness-of-fit was determined by determining the coefficient of determination (R^2) and significance was considered to be $p < .05$. These analyses support the reliability and consistency of the kinetic and thermodynamic data.

Results and Discussion

Absorption Spectrum and Wavelength Selection

A spectrophotometric analysis of UV/vis radiation covering a wavelength range from 245-400 nm has established that Vitamin C has a maximum absorbance at 285 nm, and this was therefore used for all subsequent absorbance measurements as has been reported by other researchers [29]. In order to conduct studies on Vitamin C's thermal stability, we began with measuring the absorbance values for four concentrations (0.2 - 0.8 % w/v) as shown in Table 1, where there was a concentration dependent increase in the value of the absorbance. The thermal stability study considered the effects of temperature and exposure time over two concentrations (0.8 % w/v and 0.6 % w/v), for 25 minutes at temperatures from 30 - 45 ℃; the absorbance data for these two concentrations are presented in Tables 2 and 3. For both concentrations, an increase in temperature (or time) results in a continuous decrease in the measured absorbance; the maximum values being observed at the lowest temperature (30 ℃) and minimum values at the highest temperature (45 ℃) at the end of 25 minutes exposure under heat treatment.

Table 1: Absorption values for each concentration of vitamin C

Concentration %(*w/v*)	Abs
0.8	1.97
0.6	1.60
0.4	1.23
0.2	0.89

Table 2: Absorption values for a concentration of (0.8%) after exposure to the effect of heat over time

Time (min)	5 min	10 min	15 min	20 min	25 min
Temp. °C			**Abs**		
30 °C	1.56	1.50	1.46	1.45	1.43
35 °C	1.33	1.29	1.28	1.23	1.21
40 °C	1.00	0.94	0.93	0.90	0.87
45 °C	0.95	0.88	0.86	0.78	0.66

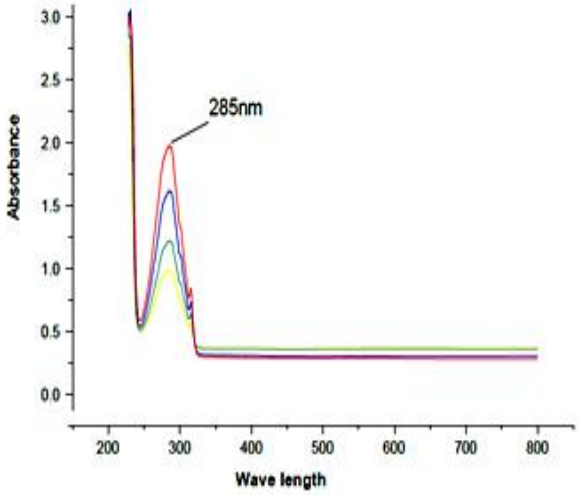
Table 3: Absorption values for a concentration of (0.6%) after exposure to the effect of heat over time

Time (min)	5 min	10 min	15 min	20 min	25 min
Temp. °C			**Abs**		
30 °C	1.45	1.43	1.41	1.38	1.35
35 °C	1.30	1.29	1.24	1.22	1.19
40 °C	0.96	0.90	0.89	0.85	0.81
45 °C	0.78	0.69	0.65	0.58	0.49

Note. Abs=Absorbance; °C= Degree Celsius; min=Minute; w/v= Weight per Volume

The Maximum Wavelength (λ max) for Vitamin C Absorption and the Standard Curve:

Figure (3) provides a UV-VIS spectrum of the sample that indicates that vitamin C has an absorbance peak at 285 nm due to characteristic electronic transitions associated with this compound [30]. This wavelength was chosen for quantitative analysis because it yields the maximum absorbance and sensitivity of the measured analytes following the Beer-Lambert Law. Absorbance was shown to linearly increase with concentration at 285 nm compared to significantly lower absorbance values that increased at wavelengths above 400 nm, indicating extremely low levels of absorbance for vitamin C within the visible portion of the electromagnetic spectrum. The limited differences in absorbance between the two curves are likely attributed to variations in experimental



conditions or partial oxidation of the vitamin C being teste regard to E_T, anything

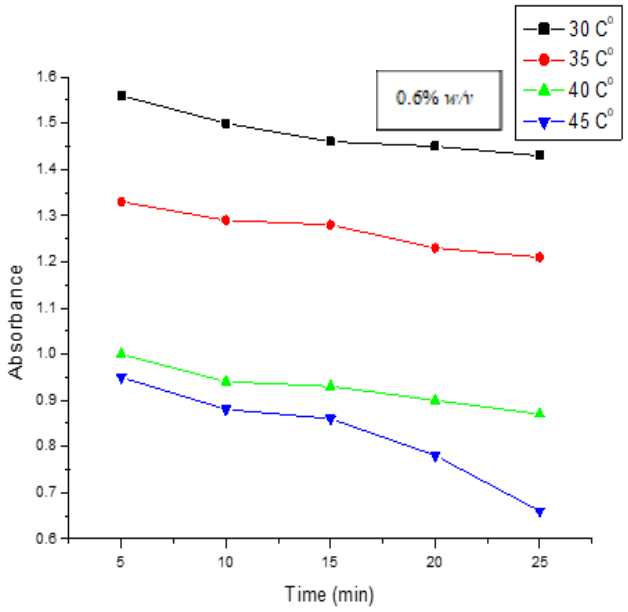
Figure 3: Absorption Curve and Wavelength of Vitamin C

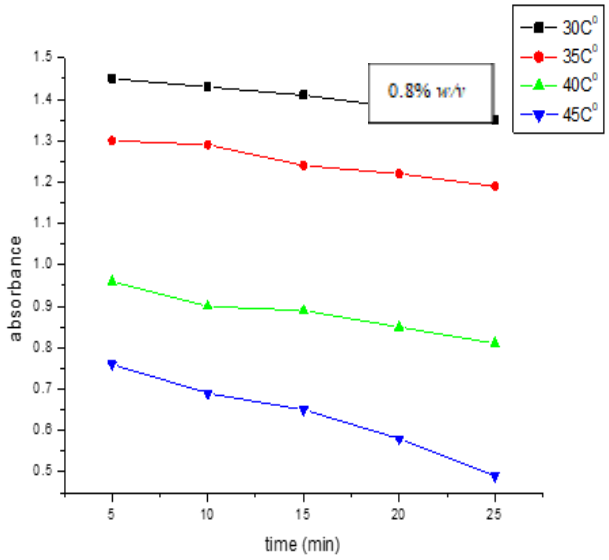
Thermodynamic Parameters Insight

Using absorbance measurements obtained from measuring Vitamin C absorbance before and after heating was plotted against temperature to calculate the transition energy (E_T) defined in equation 5 (and presented in Data Table 5). The results indicated a significant decrease in the absorbance of both concentrations of vitamin c with an increase in temperature. At 25℃ the highest values of absorbance recorded for both concentrations were 1.7262 for the 0.8%; and 1.55 for the 0.6%. At the 45℃, the lowest values were recorded 1.057; and 0.96, respectively. The λ_{max} values showed variation between 283 and 285 nm indicating that there was little effect of temperature on the electronic transition behaviour of Vitamin C. With the trend demonstrated that E_T of Vitamin C showed a very small increase from ~ 702 kJ/mol at 25℃ to ~ 706 kJ/mol at 45℃. Correlation analyses indicated strong relationships ($R^2 > 0.91$, $p < 0.05$) between temperature and absorbance reductions due to the significant impact of temperature on the stability of Vitamin C. In addition, the rate of degradation of Vitamin C over time is well defined graphically in Figure 4; with the rate of decrease in absorbance at elevated temperatures (40–45℃) being considerably greater than the rate at lower temperature (30–35℃), confirming that the degradation (decomposition kinetics) of Vitamin C will occur more rapidly at elevated temperatures than lower temperatures.

Table 5: Absorption, wavelength, and transition energy at different temperatures for vitamin C at 8.0% and 0.6%

Temperature (°C)	Absorbance (0.8% *w/v*)	Absorbance (0.6% *w/v*)	E_T (kJ/mol)
25	1.7262	1.55	701.7
30	1.6410	1.47	703.7
35	1.5500	1.45	705.7
40	1.0792	0.99	705.7
45	1.0570	0.96	705.7
Mean ± SD	1.4107 ± 0.323	1.2840 ± 0.253	704.5 ± 1.79
SE	0.144	0.113	0.80
R^2	0.923	0.918	0.748
p-value	0.009	0.011	0.060





Tables (6) and (7) provide a comprehensive summary of the degradation of vitamin C in relation to its thermodynamics and temperature dependence at both a concentration of 0.8%

Figure 4: Effect of different temperatures on absorption values over time for 0.6% and 0.8% Vitamin C

by weight and a concentration of 0.6% by weight. Additionally, since the values of the enthalpy of activation (ΔH) are all positive, it is reasonable to assume that the degradation process itself is endothermic, indicating that degradation of ascorbic acid is highly dependent upon the amount of energy required to initiate degradation and that the amount of energy required to initiate degradation is highly dependent on processing conditions [20]. Further, at lower concentrations, there is a significantly higher value of ΔH indicating that there are greater amounts of energy required to initiate degradation. The most likely reason for this phenomenon is that the solute-solvent interaction and molecular mobility of ascorbic acid will be less at lower concentrations, which is consistent with the concentration dependent stability behavior of ascorbic acid in aqueous systems as previously reported [31].

Moreover, the positive entropy (ΔS) value reflects the

increase of molecular disorder with dilution, while the negative activation entropy (ΔS‡) indicates the ordered transition state, which supports an associative and constrained degradation mechanism [32] as determining for similar reactions in solution. Furthermore, the Gibbs free energy (ΔG), which remains positive at all temperatures, indicates that the degradation is a non-spontaneous reaction; however, its decrease with increasing temperature suggests greater thermodynamic favourability at higher temperatures, which is consistent with previously reported temperature-dependent degradation of vitamin C in food systems [33]. In addition, the relatively low equilibrium constants (K_{eq}) and high activation free energy (ΔG‡ ≈ 98–100 kJ·mol⁻¹) indicate a large energy barrier and a reactant-favoured reaction system, which is consistent with previous studies of kinetics [34].Overall, the strong statistical reliability (R^2 ≈ 0.84-0.99; $p < 0.05$) of the thermodynamic models supports the validity of the thermodynamic models for vitamin C degradation and demonstrates that concentration and temperature are significant determinants of vitamin C degradation.

Table 6: Thermodynamic parameters of vitamin C degradation at different temperatures at both concentrations (0.8% and 0.6% *w/v*)

Temperature (°C)	0.8 %*w/v*			0.6 %*w/v*		
	K_{eq}	ΔG (KJ/mole)	ΔG‡ (KJ/mole)	K_{eq}	ΔG (KJ/mole)	ΔG‡(KJ/mole)
30°C	0.0035	14.21	98.42	0.0035	14.62	98.81
35°C	0.0054	13.37	99.71	0.0055	13.31	99.97
40°C	0.0090	12.25	98.25	0.0099	12.00	99.91
45°C	0.019	10.55	99.43	0.017	10.69	99.13
Mean ± SD	0.009 ± 0.007	12.60 ± 1.60	98.95 ± 0.67	0.0090 ± 0.0061	12.66 ± 1.67	99.46 ± 0.54
SE	0.0035	0.80	0.34	0.0030	0.84	0.27
CV (%)	76.09	12.70	0.68	67.42	13.18	0.54

Table 7: Thermodynamic coefficients of activation for vitamin C degradation

Parameters	0.8 %*w/v*	0.6 %*w/v*	Mean ± SD	SE	CV (%)
ΔH (kJ $^{-1}$mol^{-1})	84.35	94.045	89.20 ± 6.86	4.85	7.69
ΔS (kJ K^{-1}mol^{-1})	0.232	0.262	0.247 ± 0.021	0.015	8.58
ΔH‡ (kJ $^{-1}$mol^{-1})	89.160	93.052	91.11 ± 2.75	1.95	3.02
ΔS‡(kJ K^{-1}mol^{-1})	-0.031	-0.0206	-0.026 ± 0.007	0.005	29.5

In Table (8), vitamin C's degradation per temperature coefficient at a nominal value (Q_{10}) indicated that degradation rates were greater for lower concentrations (0.6%) than for higher (0.8%). Temperature-coefficient values were 1.346 – 3.895 for the 0.8% concentration and 1.487 – 6.202 for the 0.6% concentration demonstrating greater degradation with increasing temperatures for both concentrations, particularly the more dilute system. There was also evidence that lower concentrations had greater thermal sensitivity suggesting stability is concentration dependent. The reliability of the kinetic model fit was demonstrated using statistical measures (Mean ± SD = 3.33 ± 1.86, SE = 0.93, CV = 55.86%) and was statistically significant when $p < 0.05$ and $R^2 > 0.90$. All of this is in agreement with earlier studies demonstrating a strong relationship between temperature and the degradation of vitamin C is particularly evident when compared to dilute solutions.

Kinetic Parameters Insight

The study demonstrates that the thermal degradation of vitamin C follows first-order kinetics at each of the temperatures studied. There was a significant increase in the degradation rate constant (*K*) with increasing temperature and a corresponding decrease in half-life ($t_{1/2}$) of ascorbic acid, which supports the temperature dependence of the stability of ascorbic acid as described by the Arrhenius model. For the 0.8% *w/v* solution, the rate constant increased from 0.00416843 min⁻¹ at 30°C to 0.01883854 min⁻¹ at 45°C, whereas the half-life decreased from 166.2 to 36.8 minutes (Table 9). In addition, in the case of the 0.6% w/v solution, *k* increased from 0.00356965 to 0.02104942 min⁻¹, and the degradation half-life ($t_{1/2}$) decreased from 194.14 to 32.92 minutes. These results are consistent with previous studies that showed higher temperatures increased the degradation rates of ascorbic acid and confirmed that ascorbic acid followed first-order kinetics [35,36]. $k=Ae^{-Ea/RT}$ The Arrhenius plots (Figure 5) demonstrated a linear relationship between lnK and T1/T and validated the use of the Arrhenius equation and kinetic model used in the present study. The activation energies determined for the 0.8 and 0.6% solutions (84.35 and 94.05 kJ mol⁻¹, respectively) further demonstrate the high thermal sensitivity and susceptibility to degradation of vitamin C at elevated temperatures. As shown in Table 9, the degradation rate of vitamin C increased with temperature for both concentrations. The 0.8% w/v solution showed R^2=0.889 and the 0.6% w/v solution showed R^2=0.815, confirming good agreement with first-order kinetics. The mean *k* values were 0.01096±0.00755 and 0.00936±0.00808 min⁻¹ for 0.8% and 0.6% solutions, respectively. The obtained p-values (<0.1) indicate a noticeable effect of temperature on vitamin C degradation kinetics.

Concentration	Temperature (°C)	Q_{10}
0.8 %*w/v*	30-40°C	3.840
	35-45°C	3.895
	30-35°C	1.346
	40-45°C	1.385
0.6 %*w/v*	30-40°C	2.368
	35-45°C	4.386
	30-35°C	1.487
	40-45°C	6.202
Mean ± SD	-	3.33 ± 1.86
SE	-	0.93
CV (%)	-	55.86

Table 8: Effect of temperature on Q_{10} coefficient for vitamin C

Table 9: Kinetic parameters of the degradation of 0.6 and 0.8% vitamin C solution at each temperature

Temperature °C	0.8 (%*w/v*)			0.6 (%*w/v*)		
	k $_{min}^{-1}$	$t_{1/2\ min}$	A $_{min}^{-1}$	k $_{min}^{-1}$	$t_{1/2\ min}$	A $_{min}^{-1}$
30°C	0.00416843	166.2	1.43×10^{12}	0.00356965	194.14	5.72×10^{13}
35°C	0.0048363	143.3	9.62×10^{12}	0.00435267	159.213	3.81×10^{13}
40°C	0.01600585	43.3	1.88×10^{12}	0.00845201	81.99	4.12×10^{13}
45°C	0.01883854	36.8	1.33×10^{12}	0.02104942	32.92	5.81×10^{13}
Mean ± SD	0.01096 ± 0.00755	97.40 ± 67.29	3.57×10^{12} ± 3.90×10^{12}	0.00936 ± 0.00808	117.07 ± 73.88	4.87×10^{13} ± 0.95×10^{13}
SE	0.00378	33.65	1.95×1012	0.00404	36.94	0.475×10^{13}

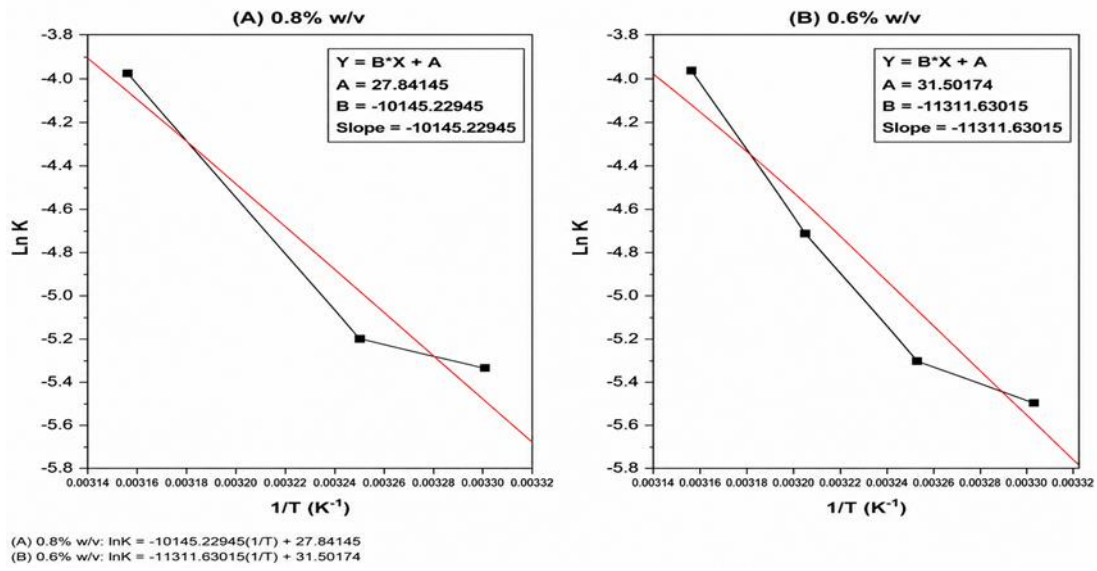


Figure 5: The slope of the reaction constant (lnK) versus the reciprocal of the temperature for vitamin C solutions (0.8% and 0.6%)

Conclusion

This research offers a detailed analysis of the kinetic and thermodynamic characteristics of vitamin C (ascorbic acid) degradation in aqueous solutions at varying temperatures and concentrations. The findings showed that the degradation follows a first-order reaction under all conditions studied, and the consistent relationship of increasing temperature with increasing k and decreasing $t_{1/2}$ is evidence of this. The calculated kinetic parameters (k, $t_{1/2}$, A) provided clear evidence that temperature is the primary control of vitamin C degradation rate. The Q_{10} values confirmed the strong thermal sensitivity of vitamin C, especially at a concentration of 0.6% *w/v*, and indicated that diluting increases its susceptibility to degradation from heat. The statistical parameters supported the validity of the kinetic model, with acceptable linearity (R^2 values) being found to confirm Arrhenius behaviour and support a first-order interpretation. The thermodynamic analysis demonstrated that the reaction is endothermic, with positive ΔH values, and that the degradation reaction is non-spontaneous and requires a continuous supply of energy, as indicated by the positive ΔG values [37].

The relatively high activation energy (E_a) and Gibbs activation energy (ΔG‡) further confirmed the presence of a significant energy barrier governing the reaction. Additionally, entropy (ΔS and ΔS‡) values reflected changes in molecular disorder and a more ordered transition state during degradation, consistent with structured reaction pathways. From an industrial and practical perspective, these findings are highly significant for the food, pharmaceutical, and cosmetic industries, where vitamin C is widely used. The combined kinetic and thermodynamic results clearly demonstrate that vitamin C is highly unstable under elevated temperatures, leading to rapid loss of activity, reduced product quality, and shortened shelf life if not properly controlled.

Recommendations for Practice

Based on the experimental results, several practical recommendations can be proposed.

- To mitigate the degradation, store vitamin C products in a refrigerated or controlled low-temperature environment.
- Packaging should be thermally insulated and light-shielding to reduce the environmental impact during storage and transport.
- Employ stabilization methods such as encapsulation or protective formulations to enhance heat degradation resistance.
- Stringent temperature control throughout the manufacturing, storage and distribution chains (cold-chain management where applicable).
- Avoid prolonged exposure of vitamin C solutions to ambient or elevated temperatures during preparation and use.

In conclusion, the present study provides convincing evidence that temperature control is the key factor for improving the stability, shelf life and efficacy of vitamin C-based products in industrial and pharmaceutical applications.

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