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KINETICS OF NUTRITIONAL DEGRADATION OF APPLE JUICE INFLUENCED BY STORAGE CONDITIONS

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Abstract

The stability of nutrients in apple juice during storage is critical for maintaining its nutritional quality and shelf life. This study investigated the kinetics of vitamin C (ascorbic acid) and polyphenol degradation in pasteurized apple juice under varying storage temperatures (4°C, 25°C, and 35°C) over 60 days. Degradation followed first-order reaction kinetics, with rate constants (k) determined experimentally. The Arrhenius equation was applied to model the temperature dependence of degradation, revealing activation energies (E_a) for vitamin C and for polyphenols, indicating higher thermal sensitivity of vitamin C. A Q10 analysis was used in order to evaluate the vitamin C and polyphenols acceleration of degradation with time and temperature. The results highlight the importance of refrigerated storage (4°C) to minimize losses, with vitamin C retention exceeding 85% after 60 days at 4°C, compared to <40% at 35°C. These findings provide actionable insights for optimizing apple juice storage conditions and predicting shelf life using accelerated shelf-life testing (ASLT).

Key words*: apple juice, Arrhenius kinetics, nutrient degradation, pasteurization, vitamin C.*

INTRODUCTION

Apple juice is one of the most widely consumed fruit juices globally, valued not only for its pleasant taste but also for its nutritional and health-promoting properties.

It is a rich source of bioactive compounds, including polyphenols (such as flavonoids and phenolic acids), vitamin C (ascorbic acid), organic acids, and dietary fibres (Boyer & Liu, 2004; Candrawinata et al., 2012).

These constituents contribute to its antioxidant, anti-inflammatory, and potential cardioprotective effects (Hyson, 2011).

However, the nutritional quality of apple juice is highly susceptible to degradation during processing and storage, influenced by factors such as temperature, oxygen exposure, light, enzymatic activity, and packaging materials (Nicoli et al., 1999). Understanding the kinetics of nutrient degradation is crucial for optimizing storage conditions, ensuring product safety, and extending shelf life while preserving its health benefits.

Nutritional Composition and Health Benefits of Apple Juice

Apple juice contains a diverse array of phytochemicals, with chlorogenic acid, epicatechin, being among the most prominent polyphenols (Kahle et al., 2005).

These compounds exhibit strong free radical-scavenging activity, which helps mitigate oxidative stress *in vivo* (Eberhardt et al., 2000).

Additionally, vitamin C, though present in moderate amounts compared to citrus juices, plays a key role in immune function and collagen synthesis (Naidu, 2003).

The presence of soluble fibres, such as pectin, further enhances its functional properties by promoting gut health and modulating lipid metabolism (Sembries et al., 2006).

Despite these benefits, the stability of these nutrients is compromised by various physicochemical and enzymatic reactions.

For instance, vitamin C is highly sensitive to heat, oxygen, and light, undergoing oxidation to dehydroascorbic acid and further irreversible degradation (Zerdin et al., 2003).

Polyphenols, particularly those with ortho-dihydroxy structures (e.g., catechins), are prone to enzymatic browning mediated by polyphenol oxidase (PPO) and non-enzymatic oxidation, leading to color changes and loss of bioactive potential (Oszmiański et al., 2007a).

Factors Influencing Nutrient Degradation and Shelf Life

The degradation kinetics of apple juice nutrients depend on multiple extrinsic and intrinsic factors:

Temperature: Elevated storage temperatures accelerate chemical and enzymatic reactions, including Maillard browning, vitamin C oxidation, and polyphenol polymerization (Rojas & Gerschenson, 2001).

Studies suggest that refrigeration (4°C) significantly slows degradation compared to room temperature (25°C) or abusive conditions (>30°C) (Patras et al., 2009).

Oxygen Exposure: Oxidation is a major cause of nutrient loss, particularly for ascorbic acid and flavonoids. Modified atmosphere packaging (MAP) and oxygen scavengers have been shown to extend shelf life by minimizing oxidative reactions (Zerdin et al., 2003).

Light Exposure: Photooxidation, especially in transparent packaging, can degrade light-sensitive compounds like flavonoids and chlorophyll derivatives (if present in cloudy juices) (Robertson, 2010). Amber or opaque packaging is recommended to mitigate this effect.

Enzymatic Activity: Residual PPO and peroxidase (POD) activity, even after pasteurization, can lead to gradual browning and phenolic degradation (Gökmen et al., 2001). High-pressure processing (HPP) and pulsed electric fields (PEF) have been explored as alternatives to thermal treatment for enzyme inactivation (Aguilar-Rosas et al., 2007; Bahaciu et al., 2015).

pH and Water Activity: Lower pH (<3.5) generally stabilizes ascorbic acid but may accelerate non-enzymatic browning in the long term (Kaanane et al., 1988).

Safety Considerations and Microbial Stability

Beyond nutrient degradation, microbial growth is a critical factor in apple juice shelf life and safety. While pasteurization (typically 85-95°C for 15-30 s) effectively eliminates vegetative pathogens (e.g., *E. coli* O157:H7, *Salmonella*), spoilage yeasts and molds can contaminate post-processing (Vantarakis et al., 2011). Additionally, heat-resistant molds (e.g., *Byssochlamys spp.*) and their mycotoxins pose a challenge, necessitating stringent hygiene and preservatives (e.g., potassium sorbate) in some formulations (Tournas et al., 2006).

Kinetic Modelling for Shelf-Life Prediction

To predict nutrient retention and product stability, kinetic models (zero-, first-, or second-order reactions) are applied based on degradation rates under varying conditions (Labuza & Riboh, 1982). For example, vitamin C loss typically follows first-order kinetics, while browning reactions may exhibit more complex behaviour (Manso et al., 2001). Arrhenius equations further correlate temperature with reaction rates, aiding in accelerated shelf-life testing (ASLT) (Corradini & Peleg, 2007).

The nutritional quality of fruit juices, including apple juice, is significantly influenced by storage conditions, which can alter their bioactive compounds, vitamins, and overall sensory properties (Nicoli et al., 1999). Apple juice is rich in polyphenols, ascorbic acid, and antioxidants, which contribute to its health benefits, such as reducing oxidative stress and inflammation (Boyer & Liu, 2004). However, these nutrients are susceptible to degradation due to factors such as temperature, light exposure, oxygen availability, and storage duration (Oszmiański et al., 2007b).

Understanding the kinetics of nutrient degradation in apple juice is essential for optimizing storage conditions and preserving its nutritional value. Previous studies have demonstrated that vitamin C degradation follows first-order kinetics, while polyphenol oxidation depends on enzymatic and non-enzymatic reactions (Zerdin et al., 2003). Additionally, Maillard reactions and browning processes can further compromise juice quality during prolonged storage (Rojas & Gerschenson, 2001).

This study investigates the kinetic behavior of key nutritional components in apple juice under different storage conditions, temperature and time variations. By modeling degradation rates,

this research aims to provide insights into shelf-life prediction of optimal storage strategies to minimize nutrient loss.

MATERIALS AND METHODS

The pasteurised apple juice sample was purchased from a retailer. The samples were kept at 4°C, 25°C and 35°C for 10, 20, 30, 40, 50 and 60 days and the level of vitamin C and total polyphenols were determined in triple.

Vitamin C determination with 2,6-dichlorophenolindophenol (DCPIP)

Titration method with 2,6-dichlorophenolindophenol (DCPIP), based on the reduction of the blue dye DCPIP by ascorbic acid to a colourless form.

A standard AA solution was prepared: 10 mg of pure ascorbic acid were dissolved in 3% metaphosphoric acid (0.1 mg/mL). 5 mL standard AA were introduced into a flask and titrated with DCPIP from a burette until a faint pink color persisted for 15 sec. The volume of DCPIP used was noted (V_{std}).

DCPIP factor (F) was calculated with the formula:

$$F = \frac{mg\ AA\ in\ standard}{Volume\ DCPIP\ (mL)} = \frac{0.5\ mg}{V_{std}}$$

Extraction of vitamin C from apple juice: 10 g apple juice were blended with 50 mL 3% metaphosphoric acid, then centrifuge (5,000 × g, 10 min). Titration: 5–10 mL filtrate was introduced into a flask, and titrated with DCPIP until faint pink endpoint. The volume used for titration was noted (V_{sample}).

The amount of vitamin C was calculated with the following formula:

$$mg\ Vitamin\ C/100\ g = \frac{V_{sample} \cdot F \cdot Total\ extract\ volume\ (mL)}{Sample\ weight\ (g)} \cdot 100$$

Determination of Total Phenolic Content (TPC) by Folin-Ciocalteu

Assay quantified spectrophotometrically (765 nm) based on the reduction of Folin-Ciocalteu reagent by phenolic compounds, producing a blue chromophore (Singleton & Rossi, 1965). Apple juice samples were diluted (1:10) with 70% ethanol. Vortex, centrifuge (8,000 × g, 10 min). 0.5 mL diluted sample + 2.5 mL Folin- Ciocalteu (diluted 1:10 with water) then incubated (5 min, dark). After that, 2 mL Na_2CO_3 (20%) were added and the samples were incubated (30 min, 25°C, dark). Absorbances were measured at 765 nm vs. blank (water instead of sample).

Calibration Curve was prepared with gallic acid standards (0-500 µg/mL). Plot absorbance vs. concentration ($R^2 \geq 0.995$).

The amount of total polyphenolic compounds was calculated with the following formula:

$$TPC\ (mg\ GAE/100\ mL) = \frac{C \cdot V_{extract} \cdot DF}{W_{sample}} \cdot 100$$

C - gallic acid equivalent (GAE) concentration (mg/mL)

DF - dilution factor

Kinetics of nutrient degradation

The Arrhenius equation was used to model the kinetics of temperature dependence of nutrient degradation (e.g., vitamin C and polyphenols).

The Arrhenius equation describes how the rate constant (k) of a chemical reaction depends on temperature (T):

$$k = A \cdot e^{-\frac{E_a}{RT}}$$

k - reaction rate constant (e.g. for vitamin C and polyphenols degradation);

A - pre-exponential factor (frequency of collisions, s^{-1});

E_a - activation energy (J/mol);

R - universal gas constant (8.314 J/mol·K);

T - absolute temperature (Kelvin, K).

Nutrient degradation often follows first-order kinetics:

$$\frac{dC}{dt} = -k \cdot C$$

$$C(t) = C_0 \cdot e^{-k \cdot T}$$

C - nutritent concentration at time, t;

C_0 - initial concentration;

k - degradation rate constant (from Arrhenius equation).

By combining the two equations, it can be predicted nutrient loss over time at different stirage/procesing temperatures.

Most nutrient degradations are first-order (log-linear loss over time).

Retention of the nutrient during storage is the amount of the final concentration reported to the initial one, in %.

$$Retention\ (\%) = \frac{C_t}{C_0} \cdot 100$$

Degradation is calculated with the formula:

$$Degradation = 100 - Retention\ (\%)$$

Experiments were conducted at multiple temperatures (4, 15, 25 and 35°C), then it was plotted ln(k) vs. 1/T (Arrhenius plot) and then E_a and A were calculated from the graph plot slope ($-E_a/R$) and intercept (lnC). The Arrhenius-derived k was then used to calculate nutrient retention (%) at any temperature.

RESULTS AND DISCUSSIONS

Kinetics in vitamin C degradation during storage of apple juice

The level of vitamin C determined in apple juice samples stored at 4°C, 15°C, 25°C and 35°C for 0 to 60 days is shown in Table 1. For calculations and dimensional analysis correctness, time is represented in minutes.

Table 1. Vitamin C amount in apple juice samples (mg/100 g product)

Vitamin C, mg/100 g				
Temperature, °C / Time (min)	4	15	25	35
0	0.900	0.900	0.900	0.900
14400	0.854	0.789	0.702	0.702
28800	0.823	0.753	0.612	0.612
43200	0.802	0.678	0.543	0.543
57600	0.771	0.621	0.476	0.476
72000	0.756	0.591	0.425	0.425
86400	0.744	0.573	0.401	0.401

In order to determine the influence of each temperature and denaturation kinetics, Arrhenius equation was used the following steps are made:

It is calculated the C/C_0 ratio (level of ascorbic acid (C) after exposure to temperature, for each period of time, reported to initial level of ascorbic acid content, C_0), then the $\ln(C/C_0)$. These data are inserted in a graphical representation of ln (C/C0) = f (time) at each temperature.

Table 2. Determination of C/C_0 and $\ln(C/C_0)$ values for apple juice samples (in order to apply the Arrhenius equation)

Temperature, °C / Time (min)	4		15		25		35	
	C/C_0	$\ln(C/C_0)$	C/C_0	$\ln(C/C_0)$	C/C_0	$\ln(C/C_0)$	C/C_0	$\ln(C/C_0)$
0	1	0	1	0	1	0	1	0
14400	0.9520	-0.0492	0.8830	-0.1244	0.7650	-0.2679	0.5890	-0.5293
28800	0.9010	-0.1043	0.7960	-0.2282	0.6240	-0.4716	0.3820	-0.9623
43200	0.8570	-0.1543	0.7120	-0.3397	0.5030	-0.6872	0.2480	-1.3943
57600	0.8100	-0.2107	0.6350	-0.4541	0.4010	-0.9138	0.1530	-1.8773
72000	0.7680	-0.2640	0.5630	-0.5745	0.3270	-1.1178	0.0950	-2.3539
86400	0.7250	-0.3216	0.4980	-0.6972	0.2640	-1.3318	0.0510	-2.9759

Next steps in the evaluation of degradation kinetics, is to represent the ln(C/C0) function of time for each temperature. The equation is generated with Trendline function of Excel programme for linear evolution of the coordinates.

Accordingly, in Arrhenius equation, the reaction rate constant, k can be determined by the line equation, k = minus equation slope. For the situation of juice storage at 4°C (Figure 1), the equation is y = -4E-06x + 0.0031, so k = 4E-06, which means, k=0.000004.

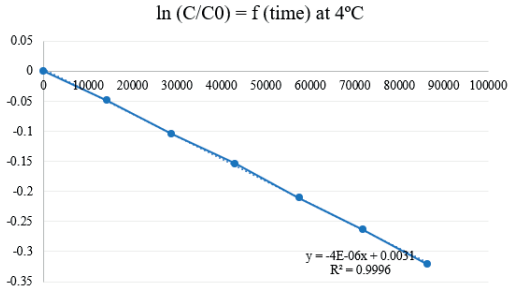

Figure 1. Representation of ln(C/C0) = f(time) at 4°C in order to determine the reaction rate

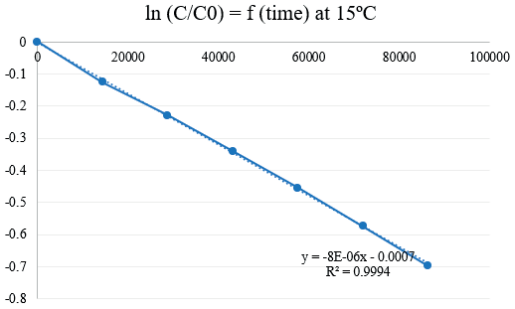

Figure 2. Representation of ln(C/C0) = f(time) at 15°C in order to determine the reaction rate

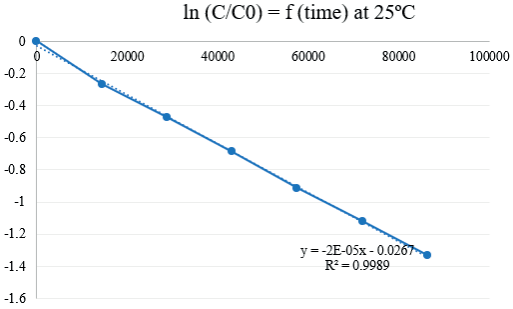

Figure 3. Representation of ln(C/C0) = f(time) at 25°C in order to determine the reaction rate

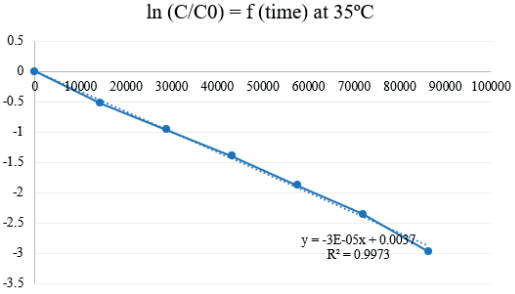

Figure 4. Representation of ln(C/C0) = f(time) at 35°C in order to determine the reaction rate

Considering the same calculation procedure, the reaction rate constant, k, were determined and the results are shown in Table 3.

The next step of the calculation is to represent the evolution of lnk function of 1/T and to identify the activation energy, Ea (Table 4).

Table 3. The reaction rate constant based on temperature

t °C	T, K	k
4	277.15	0.000004
15	288.15	0.000008
25	298.15	0.00002
35	308.15	0.00003

Table 4. Calculation of lnk and 1/T parameters

1/T	lnk
0.0036	-12.4292
0.0035	-11.7361
0.0034	-10.8198
0.0032	-10.4143

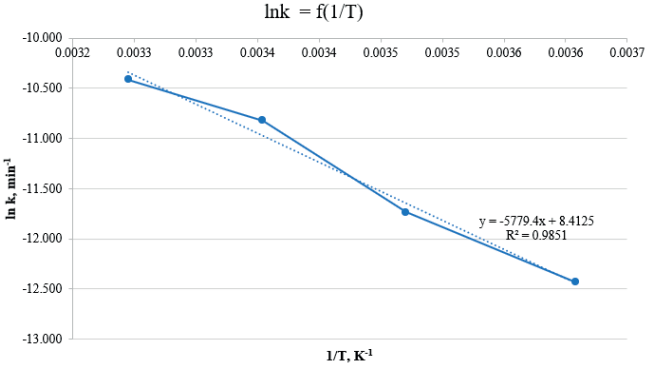

Figure 5. The evolution of the reaction rate constant (lnk) with temperature (1/T) for vitamin C degradation

From the equation shown in Figure 4 which represents the influence of temperature on reaction rate constant, the Ea/R ratio it was determined.

Table 5. Calculation of the activation energy Ea, kJ/mol for vitamin C degradation

Parameter	Unit of measure	Value	
-Ea/R	K	-5779.4	$-\frac{E_a}{R}$ → LN (A)
Ea/R	K	5779.4	
R – universal gas constant	J/mol K	8.314	
Ea	J/mol	48,049.93	
Ea – activation energy	kJ/mol	**48.05**	**y = -5779.4x + 8.4125**
LN(A)		**8.4215**	$A = e^{8.4125} = \mathbf{4503.01\ min^{-1}}$

The activation energy (E_a) represents the energy barrier that must be overcome for vitamin C degradation to occur. The measure unit is kJ/mol. Higher E_a = stronger temperature dependence (i.e., degradation accelerates more sharply as temperature rises).
In apple juice storage, the range of $E_a \approx$ 60- 65 kJ/mol (Vikram et al., 2005; Aadil et al., 2019).
High E_a: Vitamin C degradation is highly sensitive to temperature changes.
For example, a 10°C increase (e.g., from 4°C to 14°C) may double the degradation rate ($Q_{10} \approx$ 2.5).
Low E_a (<30 kJ/mol): Weak temperature dependence (e.g., some polyphenols).
Practical Impact: at 4°C (277 K): slow degradation (long shelf life), at 35°C (308 K): rapid degradation (short shelf life).
The **pre-exponential factor (A)**, also called the **frequency factor**, is a critical parameter in the Arrhenius equation that reveals fundamental insights about reaction dynamics:

$$k = A \cdot e^{-\frac{E_a}{RT}}$$

A represents the collision frequency (for gas-phase reactions) or attempt rate (for condensed phases) of molecules in the correct orientation for reaction. While Ea governs temperature sensitivity, A sets the "baseline" reaction speed when T→∞.
For complex systems (e.g., foods), in degradation reactions, A encodes molecular mobility in the matrix (e.g., water activity affects diffusion), catalytic effects (e.g., metals, enzymes), pH-dependent protonation states.

Table 6. The role of A value in practice

Application	Interpretation of A	Example
Shelf-life prediction	High A - faster degradation, even at low E_a	Vitamin C in contaminated juice degrades rapidly despite moderate E_a.
Process optimisation	Low A - longer processes time needed	Pasteurization of viscous liquids requires higher temperature to compensate for low molecular mobility (low A)
Quality control	A value shifts indicate formulation changes (e.g. antioxidants added)	Adding chelators reduces A values for oxidation reactions by sequestering metals

We calculated the A value and the results shown $A = e^{8.4125} = 4503.01\ min^{-1}$, which is **$A=6.48 \cdot 10^6\ day^{-1}$** for vitamin C degradation, which suggests: high frequency of reactive events are likely due to: high solubility of vitamin C → frequent reactant encounters, susceptibility to multiple degradation pathways (oxidation, hydrolysis).
Typical A for vitamin C: 10^5-$10^8\ day^{-1}$, our determined value falls within expected range. Deviations may reflect differences in juice matrix (e.g., polyphenols acting as pro-oxidants) (Tikekar et al., 2011).
The reaction rate constant analysis and comparison can be used in order to identify the speed of denaturation of a food product, which is directly related to shelf-life prediction.

Table 7. The rate of decreasing of vitamin C in apple juice due to storage conditions and time

t °C	k	$\frac{k_{T2}}{k_{T1}}$	Comments
4	0.000004		
15	0.000008	$\frac{k_{15}}{k_4} = \frac{0.000008}{0.000004} = 2$	Vitamin C in apple juice degrades 2 times faster at 15°C than at 4°C
25	0.00002	$\frac{k_{25}}{k_4} = \frac{0.00002}{0.000004} = 5$	Vitamin C in apple juice degrades 5 times faster at 25°C than at 4°C
35	0.00003	$\frac{k_{35}}{k_4} = \frac{0.00003}{0.000004} = 7.5$	Vitamin C in apple juice degrades 7.5 times faster at 35°C than at 4°C

Kinetics in total polyphenols degradation during storage of apple juice

The level of total polyphenols was determined in apple juice samples stored at 4°C, 15°C, 25°C and 35°C for 0 to 60 days is shown in Table 8. For calculations and dimensional analysis correctness, time is represented in minutes.

Table 8. Total polyphenols content of apple juice samples (mg GAE/100 mL)

Total polyphenols content (TPC) (mg GAE/100 mL)				
Temperature, °C / Time (min)	4	15	25	35
0	268.75	268.75	268.75	268.75
14400	264.72	258.54	249.13	229.51
28800	260.96	252.09	235.16	199.41
43200	256.93	242.68	220.38	171.46
57600	252.63	234.08	205.59	147.54
72000	248.06	224.41	188.66	124.43
86400	243.22	215.81	174.15	104.01

Table 9. Determination of C/C_0 and $\ln(C/C_0)$ values for apple juice samples (in order to apply the Arrhenius equation)

Total polyphenols content (TPC), mg GAE/100 mL								
Temperature, °C / Time (min)	4		15		25		35	
	C/C_0	$\ln(C/C_0)$	C/C_0	$\ln(C/C_0)$	C/C_0	$\ln(C/C_0)$	C/C_0	$\ln(C/C_0)$
0	1	0	1	0	1	0	1	0
14400	0.9850	-0.0151	0.9620	-0.0387	0.9270	-0.0758	0.8540	-0.1578
28800	0.9710	-0.0294	0.9380	-0.0640	0.8750	-0.1335	0.7420	-0.2984
43200	0.9560	-0.0450	0.9030	-0.1020	0.8200	-0.1985	0.6380	-0.4494
57600	0.9400	-0.0619	0.8710	-0.1381	0.7650	-0.2679	0.5490	-0.5997
72000	0.9230	-0.0801	0.8350	-0.1803	0.7020	-0.3538	0.4630	-0.7700
86400	0.9050	-0.0998	0.8030	-0.2194	0.6480	-0.4339	0.3870	-0.9493

In order to determine the influence of each temperature and denaturation kinetics, Arrhenius equation was used the following steps are made:

It is calculated the C/C_0 ratio (level of total polyphenols TPC (C) after exposure to temperature, for each period of time, reported to initial level of TPC (C_0), then the $\ln(C/C_0)$.

These data are inserted in a graphical representtation of ln (C/C0) = f (time) at each temperature.

Next steps in the evaluation of degradation kinetics, is to represent the ln(C/C0) function of time for each temperature. The equation is generated with Trendline function of Excel programme for linear evolution of the coordinates.

Accordingly, in Arrhenius equation, the reaction rate constant, k can be determined by the line equation, k = minus equation slope. For the situation of juice storage at 4°C (Figure 1), the equation is y = -1E-06x - 0.0166, so k = 1E-06, which means, k=0.000001

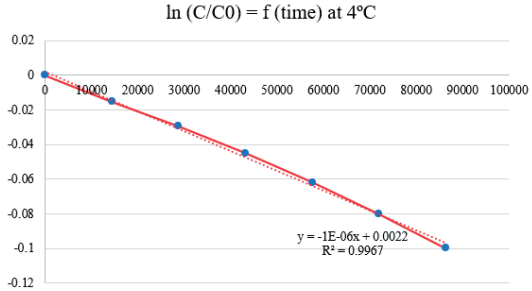

Figure 6. Representation of ln(C/C0) = f(time) at 4°C in order to determine the reaction rate

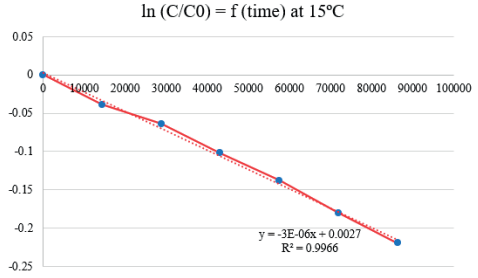

Figure 7. Representation of ln(C/C0) = f(time) at 15°C in order to determine the reaction rate

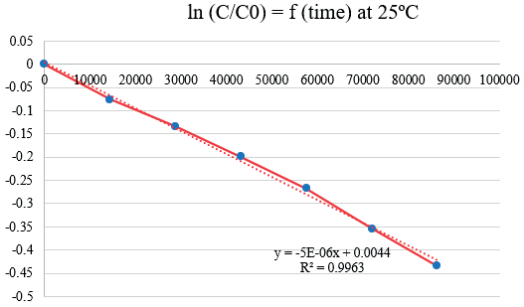

Figure 8. Representation of ln(C/C0) = f(time) at 25°C in order to determine the reaction rate

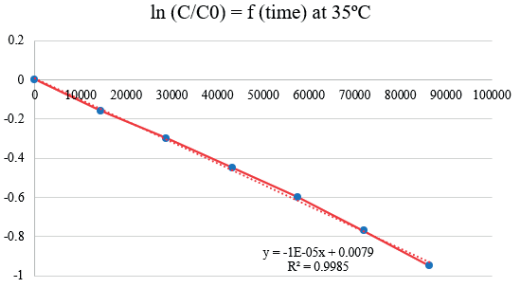

Figure 9. Representation of ln(C/C0) = f(time) at 35°C in order to determine the reaction rate

The reaction rate constant, k, were determined and the results are shown in Table 10.
The next step of the calculation is to represent the evolution of lnk function of 1/T and to identify the activation energy, Ea (Table 11).

Table 10. The reaction rate constant based on temperature

t °C	T, K	k
4	277.15	0.000001
15	288.15	0.000003
25	298.15	0.000005
35	308.15	0.00001

Table 11. Calculation of lnk and 1/T parameters

t °C	T, K	1/T	k	lnk
4	277.15	0.0036	0.000001	-13.815511
15	288.15	0.0035	0.000003	-12.716898
25	298.15	0.0034	0/000005	-12.206073
35	308.15	0.0032	0.00001	-11.512925

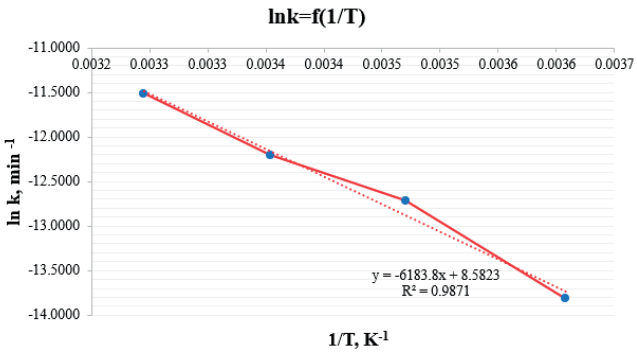

Figure 10. The evolution of the reaction rate constant (lnk) with temperature (1/T) for TPC degradation

From the equation shown in Figure 10 which represents the influence of temperature on reaction rate constant, the Ea/R ratio it was determined.

Table 12. Calculation of the activation energy Ea, kJ/mol, for TPC degradation

Parameter	Unit of measure	Value	Formula
$-E_a/R$	-6183.8	K	
E_a/R	6183.8		
R	8.314	**J/mol K**	
E_a	**51,412.11**	**J/mol**	
E_a	**51.41**	**kJ/mol**	

We calculated the A value and the results shown $A = e^{8.4125} = 5{,}336.37\ min^{-1}$, which is **$A=7.68 \cdot 10^6\ day^{-1}$** for total polyphenol degradation).

The pre-exponential factor (A) for polyphenol degradation in apple juice typically falls within the range of 10^4–10^7 day^{-1} (depending on the specific polyphenol class and storage and processing conditions. Our values are falling into this area (Krapfenbauer et al., 2007).

The reaction rate constant analysis and comparison can be used in order to identify the speed of denaturation of a food product, which is directly related to shelf life prediction.

Table 13. The rate of decreasing of total polyphenols (TPC) in apple juice due to storage conditions and time

t °C	k	$\frac{k_{T2}}{k_{T1}}$	Comments
4	0.000001		
15	0.000003	$\frac{k_{15}}{k_4} = \frac{0.000003}{0.000001} = 3$	TPC in apple juice degrades 3 times faster at 15°C than at 4°C
25	0/000005	$\frac{k_{25}}{k_4} = \frac{0.00005}{0.000001} = 5$	TPC in apple juice degrades 5 times faster at 25°C than at 4°C
35	0.00001	$\frac{k_{35}}{k_4} = \frac{0.0001}{0.000001} = 10$	TPC in apple juice degrades 10 times faster at 35°C than at 4°C

A high A (e.g., 10^6 day^{-1}) means polyphenols degrade rapidly even at low temperatures (e.g., quercetin in stored juice). Formulators can reduce A by adding antioxidants (e.g., ascorbic acid) or chelators (e.g., citrate).

CONCLUSIONS

This study reveals that vitamin C and polyphenols in apple juice degrade following first-order kinetics, with temperature being the dominant factor, with degradation rates increasing significantly at higher storage temperatures (4°C to 35°C).

Vitamin C shows greater thermal sensitivity (E_a=48.05 kJ/mol) than polyphenols (E_a=51.41 kJ/mol), though quercetin glycosides degrade fastest among polyphenols.

Key findings include:

- Each 10°C temperature increase accelerates degradation 2-3× (vitamin C) and 3-10× (polyphenols)
- Refrigeration (4°C) preserves >85% vitamin C and >90% polyphenols for 60 days versus <60% retention at 35°C
- Mild pasteurization (85°C, ≤30s) optimally balances microbial safety with nutrient preservation.

The validated Arrhenius models (R^2>0.99) enable precise shelf-life predictions, while oxygen-barrier packaging and potential non-thermal methods offer practical preservation solutions.

These findings provide actionable guidance for maintaining nutritional quality in apple juice production and storage.

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REFERENCES

Aadil, R. M., Zeng, X. A., Pateiro, M., Lorenzo, J. M., & Liu, Z. W. (2019). Impact of thermal and non-thermal processing on bioactive compounds and antioxidant activity of apple juice. *Food Chemistry*, *271*, 329–335. https://doi.org/10.1016/j.foodchem.2018.07.171

Aguilar-Rosas, S. F., Ballinas-Casarrubias, M. L., Nevárez-Moorillón, G. V. & Hernández-López, D. (2007). Effect of high-pressure processing on polyphenol oxidase and peroxidase activities in apple juice. *Food Chemistry*, *102*(2), 478–483. https://doi.org/10.1016/j.foodchem.2006.05.059

Bahaciu G.V., Segal R. & Nicolae C.G., (2015). Improvement of the antioxidant activity of soybean (*Glycine max*.) by biotechnological processing. *Romanian Biotechnological Letters*, 20(2), ISSN 1224-5984, http://www.rombio.eu/rbl2vol20/4.pdf

Boyer, J., & Liu, R. H. (2004). Apple phytochemicals and their health benefits. *Nutrition Journal, 3*(1), 5.

Candrawinata, V. I., Blades, B. L., Golding, J. B., Stathopoulos, C. E., & Roach, P. D. (2012). Effect of clarification on the polyphenolic compound content and antioxidant activity of commercial apple juices. *International Food Research Journal*, *19*(3), 1055–1061.

Corradini, M. G., & Peleg, M. (2007). *Critical Reviews in Food Science and Nutrition, 47*(1), 99–127.

Eberhardt, M. V., Lee, C. Y., & Liu, R. H. (2000). Antioxidant activity of fresh apples. *Nature*, *405*(6789), 903–904.

Gökmen, V., Borneman, Z., & Velioglu, Y. S. (2001). Kinetics of enzymatic browning in cut apple slices. *Journal of Food Engineering*, *48*(1), 51–59. https://doi.org/10.1016/S0260-8774(00)00139-4

Hyson, D. A. (2011). A comprehensive review of apples and apple components and their relationship to human health. *Advances in Nutrition*, *2*(5), 408–420.

Kaanane, A., Labuza, T. P., & Warthesen, J. J. (1988). Kinetics of nonenzymatic browning in model systems containing ascorbic acid. *Journal of Food Science*, *53*(5), 1435–1439. https://doi.org/10.1111/j.1365-2621.1988.tb09346.x

Kahle, K., Kraus, M., & Richling, E. (2005). Polyphenol profiles of apple juices. *Molecular Nutrition & Food Research*, *49*(8), 797–806. https://doi.org/10.1002/mnfr.200500021

Krapfenbauer, G., Kinner, M., Gössinger, M., Schonlechner, R., & Berghofer, E. (2006). Effect of thermal treatment on the quality of cloudy apple juice. *Journal of Agricultural and Food Chemistry*, 54(15), 5453–5460. https://doi.org/10.1021/jf060685o

Labuza, T. P., & Riboh, D. (1982). Theory and application of Arrhenius kinetics to food stability data. *Journal of Food Science*, *47*(1), 144–159. https://doi.org/10.1111/j.1365-2621.1982.tb11043.x

Naidu, A. (2003). Vitamin C in human health and disease is still a mystery? An overview. *Nutrition Journal*, *2*, 7.

Nicoli, M. C., Anese, M., & Parpinel, M. (1999). Influence of processing on the antioxidant properties of fruit and vegetables. *Trends in Food Science & Technology, 10*(3), 94–100.

Oszmiański, J., Wojdyło, A., & Kolniak, J. (2007b). Effect of processing and storage on the content of polyphenols in cloudy apple juice. *Journal of Agricultural and Food Chemistry*, *55*(26), 10840–10845.

Oszmiański, J., Wolniak, M., Wojdyło, A., & Wawer, I. (2007a). Comparative study of polyphenolic content and antiradical activity of cloudy and clear apple juices. *Journal of the Science of Food and Agriculture, 87*(4), 573–579.

Patras, A., Brunton, N. P., Tiwari, B. K., Swiderski, F., & O'Donnell, C. P. (2009). Effect of thermal processing on anthocyanin stability in foods; mechanisms and kinetics of degradation and recent aspects of stabilization. *Trends in Food Science & Technology*, *20*(8), 341–353. https://doi.org/10.1016/j.tifs.2009.04.009

Rojas, A. M., & Gerschenson, L. N. (2001). Vitamin C destruction in aqueous model systems and in fruit juices in the presence of flavonoids. *Journal of the Science of Food and Agriculture, 81*(8), 717–724.

Sembries, S., Hess, R., & Glitscher, R. (2006). Effects of apple pectin on plasma lipids in subjects with hypercholesterolemia. *Nutrition Research*, *26*(1), 17–23.

Singleton, V. & Rossi, J. (1965) Colorimetry of Total Phenolic Compounds with Phosphomolybdic-Phosphotungstic Acid Reagents. *American Journal of Enology and Viticulture*, 16, 144–158.

Tikekar, R. V., Anantheswaran, R. C., & LaBorde, L. F. (2011). Degradation kinetics of vitamin C in fruit juices as a function of oxygen and temperature. *Journal of Food Science*, 76(6), C861–C868. https://doi.org/10.1111/j.1750-3841.2011.02316.x

Tournas, V., Katsoudas, E., & Miracco, E. J. (2006). Moulds, yeasts, and aerobic plate counts in apple juice concentrates obtained from retail and manufacturing sources. *Journal of Food Protection*, 69(2), 397–401. https://doi.org/10.4315/0362-028X-69.2.397

Vantarakis, A., Komitopoulou, E., Tremouli, A., Papadomichelakis, G., & Mavridou, A. (2011). Microbiological quality of fruit juices sold in the Greek market. *International Journal of Food Microbiology*, *144*(3), 570–574. https://doi.org/10.1016/j.ijfoodmicro.2010.11.025

Vikram, V. B., Ramesh, M. N., & Pura Naik, J. (2005). Kinetics of thermal degradation of vitamin C in cloudy apple juice. *Journal of Agricultural and Food Chemistry*, *53*(8), 3075–3080. https://doi.org/10.1021/jf048386k

Zerdin, K., Rooney, M. L., & Vermuë, J. (2003). The vitamin C content of orange juice packed in an oxygen scavenger material. *Food Chemistry, 82*(3), 387–395.