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Kinetic Modelling of the Thermal Degradation of Vitamin C and Carotenoids During Pasteurization in Tomato Juice

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Abstract

Juice ranks among the most favored beverage products globally. Consumption of tomato juice is known as a functional food which provides advantages for several functions in the body. Tomato juice is often processed using pasteurization to extend its shelf life and to prevent deterioration during storage and distribution. The negative aspects of the pasteurization process in tomato juice processing are the degradation of beneficial components due to increased temperatures. Additionally, an increase in processing time also causes degradation, even though the temperature remains constant. This research aimed at determining the degradation kinetic of vitamin C and carotenoids bioactive compounds and its antioxidant activity in tomato juices throughout pasteurization, including the reaction rate as a function of process temperature at 60 °C, 70 °C, 80 °C, and 90 °C. This research examined the impact of temperature and pasteurization treatment time on the degradation of carotenoids, vitamin C, and the reduction of antioxidant activity in pasteurized tomato juice at temperatures ranging from 60 to 90 °C. The pasteurization process significantly decreased the concentrations of vitamin C, carotenoids, and antioxidant activity ($P < 0.05$) in tomato juice. The degradation kinetics of bioactive compound in pasteurized tomato juice ~~is~~ followed first-order kinetic with the $R^2 > 0.90$, and Arrhenius models was able to explain the changes in the rate of constant degradation in each of the bioactive compounds. Vitamin C was the most heat-sensitive compound among those analyzed in this study, showing the greatest degradation during the pasteurization process of tomato juice.

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Introduction

Juice is one of the most popular beverage products in the world. Over the past years, consumption of juices has increased 21%, driven by its functional properties and lifestyle changes (Innova Market Insight, 2024). Tomato juice consumption has been known as a functional food that has benefits for several body functions, such as to prevent constipation, to maintain normal blood pressure, to maintain lipid profile, and to prevent degenerative diseases, such as cardiovascular disease (CVD), cancer, and neurodegenerative diseases (Salehi, 2019; Cheng, 2019; Li, 2020; Park, 2020). Ali et al. (2021) and Santos et al. (2019). Tomato fruits contain 30 – 39 mg/100 grams of vitamin C and 11 – 25 mg/100 grams of carotenoids. Tomato juice can be considered as natural source of bioactive compound that acts as natural antioxidants that are known to be beneficial for health, such as vitamin C, polyphenols, and carotenoids. These antioxidants compounds could neutralize reactive oxygen species (ROS) and decrease oxidative stress which can indirectly lead to metabolic syndrome (Navarro, 2018; Ali, 2021).

Tomato juice is processed using pasteurization to reduce the water content and to extend the shelf life. However, the thermal processing of tomato juice also has weaknesses such as deteriorating the bioactive compounds that are sensitive to heat (vitamin C, and carotenoid compounds) (Margean, 2020). These bioactive compounds degradation process is influenced by different factors, such as temperature, oxygen, pH and exposure to light (Zepka et al., 2009). Moreover, these bioactive compounds could lose their antioxidants activity caused by temperature used in pasteurization process. The kinetic model of these degradation bioactive compounds, including the reaction rate as a function of temperature, must be studied to predict the bioactive compound's degradation during thermal treatments.

The thermal degradation kinetics of vitamin C in fruit juice have been studied, such as by Santos et al

(2019) who explained changes in vitamin C with first-order kinetics in tomato juice thermally processed at 70 – 90 °C. Vieira et al. (2016) also reported that thermal degradation kinetics fitted with a first-order kinetics model during a pasteurization process at between 50 and 90 °C for orange juice. In another study, Dhakal et al. (2018) also reported that thermal processing of pineapple juice at 75 – 95 °C follow the first-order kinetics models.

Recently, there has been no researcher that has observed the kinetic model for degradation of antioxidant activity and bioactive content in tomato juice during the pasteurization process at temperatures ranging from 60 to 90 °C and processing times of 5, 10, 15, 20, 25, and 30 minutes. This research is expected to determine the kinetic parameters of Carotenoids, vitamin C, and its antioxidant activity in tomato juices during the pasteurization process, as a function of the process temperature. The result of this research could be used for predicting degradation rates during pasteurization process in tomato juice. It would be beneficial for tomato juice's processing industries since it would be used for arrange the best thermal processes to prevent the loss of bioactive compounds. Therefore, the objective of this research was to study the influence of temperature on the degradation of vitamin C and antioxidant activity in tomato juice during pasteurization at 60, 70, 80 and 90 °C.

Materials and Methods

Materials

The materials used in this research are tomatoes obtained from a traditional market in Belimbing Malang, with the following characteristics: red on the entire fruit surface, fruit diameter 15 ± 2 cm, and weight of 48 – 55 grams. The other materials used are petroleum ether, acetone, ethanol 96%, Na_2SO_4, DPPH 0.2 mM solution in ethanol, iodine, calcium iodide, starch solution, phenolphthalein indicator, NaOH, and distilled water. All chemical reagents used are of analytical grade and were bought from a chemical store in Malang.

Equipment

The equipment used in this study includes a juicer, a hot plate and magnetic stirrer, Spectrophotometer UV – Vis, a centrifuge, a vortex, a pH meter, Color Reader, oven, a desiccator, burette, and glassware.

Research Method

Research Design

Fresh tomato fruits were analyzed before being processed into juice. The analysis was carried out such as determination of pH, weight, carotenoid total, vitamin C, moisture content, brix and titratable acid. Fresh tomato juice that was analyzed before, then processed into juice. Tomato juice was analyzed before the pasteurization process. The analysis used in tomato juice before pasteurization process such as determination of vitamin C content, carotenoid total, and antioxidant activity. After that, the juice was pasteurized with the specific time and temperature. The tomato juice after pasteurization process then carried out with the same analysis as before the pasteurization process conducted.

Preparation of Tomato Juice

The preparation of tomato juice is based on the procedure described by Behera (2017). Ripe tomato fruits were washed. After removing the tomato fruit's stem tip, it was blanched for two minutes at 90 ˚C in boiled water, and then it quickly cooled for 1 minute in iced water. This time–temperature combination used in blanching process aims to inactivate the enzyme in the fruits. Afterward, tomato fruits were cut manually into slices. The blanched fruits were crushed and sieved in a juicer; the obtained juice was mixed with distilled water at 1:1 ratio. The juice was discarded and stored at 4 ˚C before the thermal processing. The tomato juice after pasteurization process is then analyzed in pH, titratable acidity (% citric acid), and total soluble solids (°Brix).

Tomato Juice Pasteurization Process

The pasteurization process of tomato juice is based on the procedure described by Supriyadi (2022). Temperature and time were the two variables used in this experiment. In sealed glass bottles, 100 grams of tomato juice were heated for 0, 5, 10, 15, 20, 25, and 30 minutes at 60, 70, 80, and 90 degrees Celsius in a water bath. After the pasteurization process, the glass bottles were cooled with iced water until pasteurized tomato juice reached 35 ˚C. During the pasteurization process, the glass bottles are covered with aluminium foil. All data conducted in this experiments were performed in triplicate. All samples were immediately taken to determine carotenoids, vitamin C, and antioxidant activity, as described below.

Determination of The Concentrations of Carotenoids

Carotenoids were extracted and measured using methods described by Santozet al (2017). Carotenoid concentrations in tomato juice were evaluated using a spectrophotometer. The absorbance of each solution in the petroleum ether phase was measured at 470 nm using petroleum ether as the reference in a spectrophotometer. The content of carotenoids in the samples was determined with an extinction coefficient ($E^{\%}_{1cm}$) in petroleum ether. Triplicate measurements were used to get the data. Carotenoids value is calculated using Equation 1.

$$Carotenoids = \frac{A \; x \; V \; x \; 10^6}{E^{\%}_{100} \; x \; 100 \; x \; sample \; weight \; (g)} \quad (1)$$

Where concentrations of carotenoids are in µg/g, A is the absorbance of the sample, V are volume in ml, ($E^{\%}_{1cm}$) are an extinction coefficient which has value 2500.

Determination of Vitamin C Concentration

The vitamin C content in the samples was evaluated using the methodology established by Wulandari (2021). Ten milliliters of tomato juice samples were put into a one-hundred milliliter flask, followed by the addition of distilled water to the flask. 25 ml of the diluted sample solution was put into a glass beaker, then followed by the addition of 1% amylum indicator, and afterwards, the solution was titrated with 0.01 N iodine solution. The titration volume correlates with the concentration of vitamin C.

Table 1. The physicochemical characterization of tomato juices

Property	Value	Reference Value
Moisture Content (%wb)	95.43±0.22	96.73±0.05
Soluble Solid (^{0}Brix)	4.4±0.21	4.73±0.05
Titratable Acidity (grams of Citric Acid/100 grams)	0.492±0.063	0.90±0.01
Carotenoid Concentration (µg/g)	49.84±2.9	11.74±0.10
pH	4.21±0.022	3.59±0.02
Vitamin C (mg/100g)	31.44 ±1.10	39.48±1.06

Determination of Antioxidant Activity by DPPH method

The antioxidant activity in the samples was determined using the method described by Baliyan et al. (2022). First, a 0.2 mM 2,2-diphenyl-1-picrylhydrazyl (DPPH) stock solution was made by mixing 39.4 mg of DPPH powder with 96% ethanol in an aluminum foil-covered glass. After the formation of the DPPH stock solution, sample preparation was executed according to the method described by Supriyadi (2022). 0.75 g of tomato juice samples were placed into a 25 ml flask, followed by the addition of 96% ethanol. Two mL of the diluted sample solution were placed into a glass tube, followed by the addition of one milliliter of 0.2 mM DPPH solution. The resulting mixture was incubated in a dark place for thirty minutes. The sample's absorbance was then determined using a UV-Vis spectrophotometer at a wavelength of 517 nm, with ethanol solution being as the blank. The results of measurements were obtained from triplicate measurements. The value of the antioxidant activity was calculated as in the inhibition percentage calculated in Equation 2.

$$\%IP = \frac{Ac-As}{Ac}\ x\ 100\% \quad (2)$$

Where antioxidants activity is in %, Ac—Control reaction absorbance, and As—Testing specimen absorbance.

Determination of Titratable Acid

The Titratable Acid in the samples was determined using the procedure developed by Supriyadi (2022). The 0.1 N NaOH solution must be standardized with 0.1 N oxalic acid. Pasteurized tomato juice samples were homogenized and transferred in volumes of up to 5 mL into 50 mL Erlenmeyer flasks. Subsequently, 2-3 drops of PP indicator were added and titrated with standardized 0.1 N NaOH until the solution's color transitioned to pink and remained stable for 30 s. The normality of NaOH can be determined by equation (3), and % titrated acid can be determined by equation (4)

$$N\ NaOH = \frac{Oxalic\ Acid\ mass\ x\ 2}{NaOH\ volume\ x\ 0.126} \quad (3)$$

$$\%TA = \frac{V\ NaOH\ x\ N\ NaOH\ x\ BM\ AL}{Volume\ sample\ x\ 1000}\ x\ 100\% \quad (4)$$

Determination of pH using pH Meter

30-50 ml of pasteurized tomato juice samples were used to measure the pH. The tool was turned on, then calibrated with a buffer solution of pH 4.0 and pH 7.0. After calibrating, the samples were analyzed. The results of measurements were obtained from triplicate measurements.

Determination of The Kinetic Parameters

Kurniawati (2016) and Mayer et al (2007) explained that the thermal degradation of pigment or bioactive compounds is frequently represented by a first-order reaction, as represented by equation 5.

$$C_t = C_0\, e^{-kt} \quad (5)$$

where C_0 and C_t are the concentration of the micronutrient of interest at time 0 and *t*, *k* is the rate of constant degradation (min^{-1}) or ***slope***, and *t* is the time period of the heat treatment (min).

Based on Toledo (1999), the decimal reduction time (D, min), and the thermal resistance coefficient (z, $^{\circ}$C) in evaluated bioactive compounds were calculated with equation 6-8.

$$D = \frac{\ln 10}{k} = \frac{2.303}{k} \quad (6)$$

A regression curve with the heating time as the x-axis and the log of the bioactive concentration as the y-axis could be used to calculate the D value. At each temperature, the value of D might be calculated using |1/slope|.

$$Z = \frac{T2-T1}{log\frac{Dt}{D0}} \quad (7)$$

where T is the heating's temperature. One way to find the z value is to make a regression curve with the heating temperature as the x-axis and the log of the D value at each heating temperature as the y-axis. The z value could be calculated by |1/slope|

Statistically Analysis

The data are presented as the mean value, and the research was conducted on two prepared samples. Paired t tests with a 5% significance level are performed in this experiment to determine whether the means of two paired measures are significantly different. This analysis was used to evaluate the effect of the pasteurization process on the content of bioactive compounds and antioxidant activity. Minitab 16.0 software was used to analyze the statistics.

Results and Discussion

Physicochemical Characterization of Tomato Juices

Table 1 presents the physicochemical characterization of tomato juice. The pH, soluble solids, titratable acidity, and vitamin C levels are lower, while the pH value is higher compared to what was found of Santos et al. (2019). This also occurred with the tomato moisture content parameter in this study, which was higher compared to what was reported in previous research, namely 94.67± 0.01% (Adubofuor et al., 2010). This occurred due to the various types of tomatoes that

were used. The quantity of carotenoids, vitamin C, and titratable acid are significantly influenced by genotype and environmental (eg. temperature, light, humidity, and atmospheric CO_2) factors (Tiwari et al., 2013). Based on Rouphael et al., (2012), The pre-harvest period involving the interaction of genetic, climatic, and cultural factors is a determinant of vegetable quality that can influence its nutritional composition. The pH value is higher due to the titratable acid's influence on the tomatoes used, which has a lower value. The results presented here are also in line with research on tomatoes processed at the tree-ripening phase, where the pH value increases during ripening while the titratable acidity decreases during the same phase (Anthon et al., 2011).

Effect of Pasteurization Process on Vitamin C content of Tomato Juices

During the pasteurization process, the amount of vitamin C decreased. The effect of pasteurization on tomato juices' vitamin C concentration can be seen in Figure 1. Tomato juice's vitamin C concentration was significantly decreased ($P < 0.05$) by the pasteurization process. Tomato juice pasteurized at 60, 70, 80, and 90 °C may have decreased vitamin C contents by 16.07%, 32.59%, 39%, and 51.62%, respectively, compared to the concentration prior to the procedure carried out.

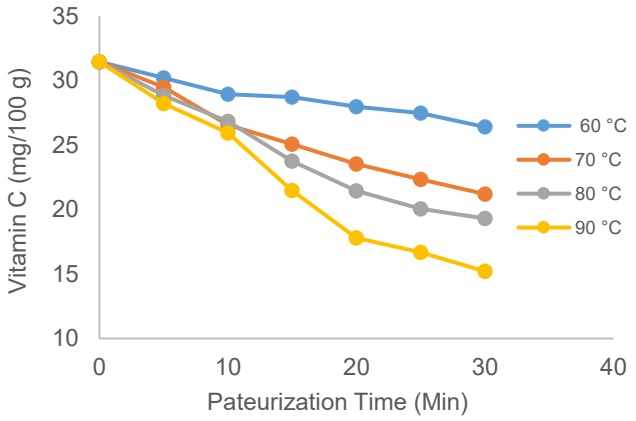

Figure 1. Effect of pasteurization process on vitamin C content of tomato juices.

Tomato juice pasteurized at 90 °C had the greatest loss in vitamin C content, whereas tomato juice treated at 60 °C had the smallest decrease. Vitamin C may break down faster and lose its antioxidant activity at higher temperatures and in the presence of oxygen. In liquid systems with high water activity (>0.980) and the presence of oxygen, the predominant pathway for ascorbic acid degradation involves its oxidation to dehydroascorbic acid, which subsequently breaks down into 2,3-diketogulonic acid (Giannakourou & Taoukis, 2021). According to Herbig and Renard (2017), vitamin C will degrade quickly as the sample's moisture content increases. As the sample's moisture level rises, vitamin C will readily break down (Herbig and Renard, 2017). Upon hydrolysis of dehydroascorbic acid, its vitamin activity is promptly lost. An increase in water activity (aw) or moisture content has been shown to enhance the degradation of ascorbic acid (Giannakourou & Taoukis, 2021). According to Santos & Silva (2008), temperature can catalyze the oxidative breakdown of ascorbic acid, which is oxidized to dehydroascorbic acid before being hydrolyzed and further oxidized.

Processing fruits and vegetables at temperatures below 100°C through pasteurization effectively preserves the products and extends their shelf life. Nevertheless, Vitamin C levels decline by 20% to 90% depending on the temperature, duration of the procedure, and exposure to oxygen (Mieszczakowska-Frąc et al., 2021). This is also demonstrated (Figure 1) by the decrease in vitamin C levels in this study, which becomes more significant at higher temperatures and with extended time.

Effect of Pasteurization Process on Carotenoids Total of Tomato Juices

Carotenoids are yellow, orange, and red pigments found in plants' leaves, flowers, and fruits. Lycopene, phytoene, and β-carotene are the most prevalent carotenoids found in tomato fruits. Carotenoids are responsible for the red color of tomato fruit. By pasteurizing tomato juices at 60, 70, 80, and 90 degrees Celsius, the amount of carotenoids may be reduced by 11.96%, 17.78%, 23.80%, and 38.06%, respectively, in comparison to the amount of carotenoids present before to the procedure. Figure 2 illustrates how tomato juices' total carotenoids are affected by the pasteurization procedure. The amount of carotenoids in tomato juice was dramatically reduced ($P < 0.05$) by the pasteurization procedure.

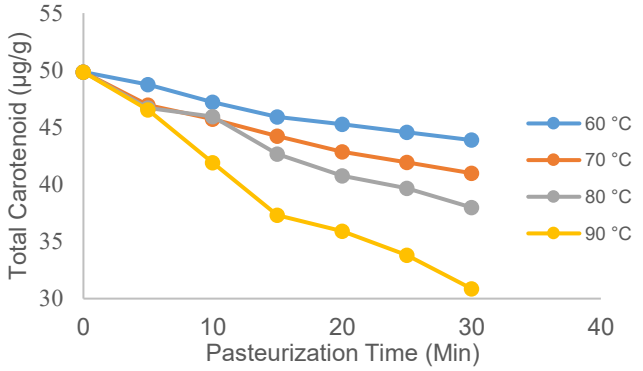

Figure 2. Effect of pasteurization process on carotenoids total of tomato juices

The method of pasteurizing tomato juice involves heating it to a high temperature in an open pan, which speeds up the oxidation of carotenoids since it exposes them to oxygen and light. Because of their highly unsaturated structure, carotenoids are very unstable and easily degraded during processing and storage. Carotenoid molecules are frequently degraded through isomerization, oxidation, and fragmentation. During isomerization, carotenoids' naturally predominant trans-form converts to the cis-form when exposed to heat, light, or acids. This transformation often leads to a reduction in their color intensity and bioavailability. Oxidation, which can be triggered by prooxidant metals, enzymes, and light, results in the formation of epoxides and other oxidative products, diminishing the antioxidant activity of carotenoids. Fragmentation, typically a consequence of advanced oxidation, breaks the carotenoid structure into

smaller compounds, further reducing their nutritional and functional properties Sharma et al. (2008); Gheonea et al. (2020).

Effect of Pasteurization Process on Antioxidant Activity of Tomato Juices

During the pasteurization process, there was a decrease in antioxidant activity. Figure 3. shows the effect of pasteurization process on antioxidant activity of tomato juices. The pasteurization process significantly decreased the antioxidant activity ($P < 0.05$) of tomato juice. Pasteurization process on tomato juices at temperature 60, 70, 80, and 90 °C could decrease the antioxidant activity respectively, 8.53%; 13.62%; 18.20%; and 29.12% compared to antioxidant activity before the process.

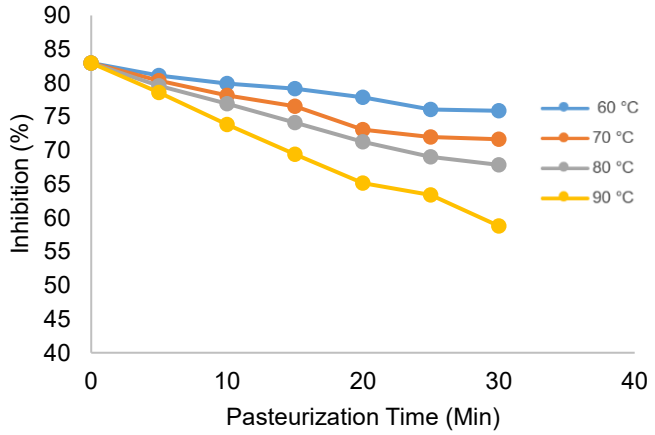

Figure 3. Effect of pasteurization process on antioxidant activity total of tomato juices

The greatest decline in antioxidant activity was seen in tomato juice pasteurized at 90°C, whereas the lowest decrease was found at 60°C. Moreover, Kathiravan et al. (2014) found that pasteurizing beetroot juice that was ready to drink reduced its antioxidant activity by 76.71% to 63.87% as opposed to the unpasteurized juice. Carotenoid and vitamin C molecules, the primary antioxidants in tomato juice, were broken down by an oxidation process that decreased their effectiveness as antioxidants, which is why antioxidant activity decreased. Phenolic compounds and carotenoids have a significant influence on antioxidant activity; thus, a decrease in these components also reflects a reduction in antioxidant activity (Vieira et al., 2018). Based on (Shen et al., 2021), the enhancement in antioxidant capacity could be linked to the elevated levels of polyphenols in cloudy apple juice, which result from the cavitation effects induced by ultrasound treatment, thereby improving the extraction and bioavailability of these compounds.

Kinetics of the thermal degradation in the carotenoids, vitamin C and antioxidant activity

To determine the degradation behavior of the vitamin C, carotenoids total, and antioxidant activity from tomato juice, we plotted the concentration of a bioactive compound versus pasteurization time as a zero-order reaction and Ln of concentration bioactive compounds versus pasteurization time as a first-order reaction. The order reaction with the following equation, which has an R^2 around 1, is the one that was selected. Figure 4 shows a comparison of R values for tomato juice's antioxidant activity, total carotenoids, and vitamin C.

Based on the data, first-order reactions have correlation coefficient values that are closer to one than zero-order reactions. Changes in the content of carotenoids, vitamin C, and antioxidant activity in tomato juice after pasteurization may be explained by the first-order kinetics of degradation, as demonstrated by the correlation coefficient of $R^2 > 0.90$ in all reactions. Several studies have revealed that the thermal degradation of numerous beneficial substances such as vitamin C, total carotenoids, and antioxidant activity followed a first-order response.

Kurniawati (2023) Santos (2019), Verbeyst (2013), and Dhakal (2018) stated that the thermal degradation of vitamin C followed a first-order reaction. Other researchers also have reported first-order kinetics of thermal degradation in carotenoids, such as Dhuique-Mayer et al. (2007) on the thermal degradation of β -carotene and β-cryptoxanthin in orange juice during thermal processing between 75 and 100 °C; Sharma et al. (2008) for lycopene in watermelon juice processed thermally between 50 and 90 °C. The values of D (min) and z (°C) explained different levels of thermal sensitivity among the bioactive compounds found in pasteurized tomato juice. The D value is often also called decimal reduction time, a measure of a compound's heat resistance. It is the time in minutes at a given

Table 2. Kinetic Parameters Obtained for Bioactive Compounds Degradation in Pasteurized Tomato Juice Between 60 and 90 °C

Compounds	T (˚C)	k (min^{-1})	D value (min)	z value (°C)
Vitamin C	60	0.0053	434.53	46.08
	70	0.0133	173.16	
	80	0.0172	133.90	
	90	0.0258	89.26	
Carotenoids Total	60	0.0043	526.32	54.35
	70	0.0063	370.37	
	80	0.0090	256.41	
	90	0.0159	144.93	
Antioxidant Activity	60	0.0030	769.23	54.36
	70	0.0052	434.78	
	80	0.0069	333.33	
	90	0.0113	204.08	

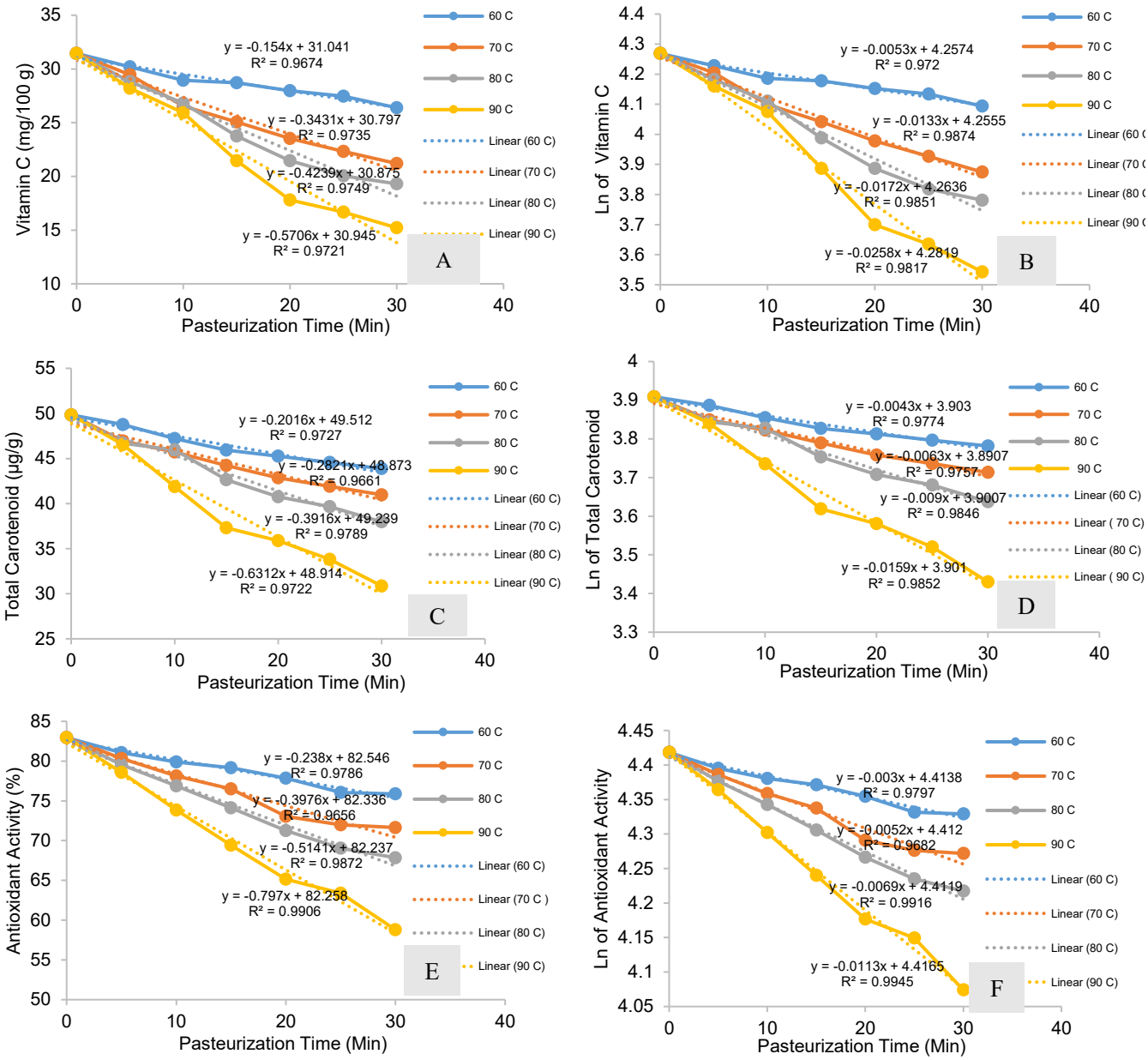

Figure 4. The difference between the R² value of zero-order and first-order reaction in the degradation behavior of (a) and (b) vitamin C, (c) and (d) carotenoids, and (e) and (f) antioxidant

temperature required to destroy 90% of the target compound. Meanwhile, the z value is the number of degrees the temperature has to be increased to achieve reduction in D value.

Table 2 shows that total carotenoids have the highest D and z values, whereas vitamin C has the lowest D value. It shows that among the evaluated bioactive components in the 60–90 °C temperature range, vitamin C exhibited the least amount of heat resistance. The lower D and z-values for vitamin C observed in this study also indicate greater thermal sensitivity compared to the values reported by Dhuique-Mayer et al. (2007) and Santos et al. (2019). Different raw materials and different heat treatments used in this experiment are the primary causes of the difference in results. The D value of vitamin C decreases as temperature increases. This effect is brought on by the fact that vitamin C will degrade rapidly at higher heating temperatures. According to Essodolom et al. (2020), ascorbic acid or vitamin C is most destroyed at temperatures between 85 and 95°C, particularly after 10 minutes of heating.

The D and z values in this experiment were represented as the total amount of carotenoids. Meanwhile, Santos et al. (2019) reported on each carotenoid separately, including zeaxanthin, lycopene, β-carotene, and α-carotene. The z value from this experiment and the z value from zeaxanthin are comparable, according to table 2. Zeaxanthin is the primary carotenoid in tomatoes, which explains these phenomena. The z value obtained in this experiment was most likely based on the largest portion of carotenoids in tomatoes. As the temperature rises, the total carotenoids D value falls. The reason for this phenomena is that carotenoids will deteriorate more quickly at greater heating temperatures. Because of their highly unsaturated structure, carotenoids are extremely unstable and prone to deterioration when processed at high temperatures.

The D value in antioxidant activity follows the

same pattern as the D value in the total amount of carotenoids and vitamin C. It indicates that when the temperature rises, antioxidant activity falls. This effect results from the pasteurization procedure, which reduces the antioxidant qualities of tomato juice by degrading the vitamin C and carotenoids. According to Suzery et al. (2020) and Vidana et al. (2017), heat might decrease the antioxidant activity of vitamin C phenolic and anthocyanin by raising the IC50 value compared to preheating settings. Jirasatid (2018) found that when heating temperatures and periods increased from 60 to 90 ˚C, the antioxidant activity (%DPPH inhibition) of pumpkin puree, which mostly contains carotenoids, was reduced.

These kinetic parameters of thermal degradation can be useful to know, predict and control the losses of carotenoid pigments, vitamin C and antioxidant activity in tomato juice during pasteurization. For example, the values of k, D, and z increased in each bioactive compound giving information on the thermal stability that would allow to estimate the losses of these bioactive compounds and arrange thermal treatments that allow to keep the highest levels of retention of these important bioactive compounds that would benefit consumers and industrial field that produces fruit juice.

Conclusion

In this study, the kinetics of pasteurized tomato juice's carotenoids, vitamin C, and antioxidant activity were assessed at temperatures ranging from 60 to 90 °C. Arrhenius models could account for variations in the rate of constant degradation in each of the bioactive compounds, and all of the assessed phytochemicals in the pasteurized tomato juice exhibited first-order kinetic thermal degradation with an $R^2 > 0.90$. The highest thermolabile substance in the pasteurized tomato juice was vitamin C. As the temperature rises, the D value of all bioactive substances and antioxidant activity decrease. In order to minimize significant losses in the nutritional value of tomato juice, the degradation of vitamin C (32.59–51.62%), carotenoids (17.78–38.06%), and antioxidant activity (13.62–29.1%) at temperatures ranging from 70 to 90 °C as observed in this study, pasteurization procedures can be optimized by selecting lower temperature–shorter time combinations. This research provides essential kinetic data that can support the design of more efficient thermal processing conditions, helping to retain higher levels of bioactive compounds and antioxidant activity in the final product

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