


Article

Degradation Kinetics of Betacyanins during the Pasteurization and Storage of Cactus Pear (*Opuntia dillenii* Haw.) Juice Using the Arrhenius, Eyring, and Ball Models

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Abstract: Betacyanin stability was assessed over temperatures ranging from 60 to 90 °C for cactus pear (*Opuntia dillenii* Haw.) juice. The juice showed a betacyanin content of 0.76 g/kg. The rate constants for the betacyanin degradation and isothermal kinetic parameters were calculated according to the following three models: Arrhenius, Eyring, and Ball. The fittings of the models were found to be close to one other with SSE values of 0.0964, 0.0964, and 0.0974, respectively. However, because the estimated parameters for the Ball equation happened to be less correlated than the parameters of the other models, this equation was then used for the simulations. The parameters for z and D_0 were 42.21 °C and 6.79×10^4 s, respectively. Betacyanins were found to resist typical heat treatment conditions ($F_{70^\circ\text{C}}$ values between 100 and 200 min), with a maximum loss of 10% when the temperature was above 80 °C. The time/temperature combinations that could assure both the safety of the product and the preservation of the betacyanins were identified. With *Enterococcus faecalis* as the reference, when the temperature was 100 °C, the pasteurization time satisfying these two conditions was 0.6 min, whereas it was 180 min when the temperature was 62 °C. The degradation of betacyanins during storage was positively correlated with temperature and was accompanied by the appearance of a brown shade.

Keywords: opuntia; betacyanins; degradation kinetic; ball model; pasteurization



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1. Introduction

The growing demand for natural products has led current research in food technology to the characterization of natural bioactive compounds. Products containing natural ingredients are generally perceived by the consumer to be better in quality, safer, and healthier than those with synthetic compounds. The legislation in Western countries strongly encourages the use of natural colorants, such as anthocyanins, carotenoids, chlorophylls, and betalains [1], in the formulation of foods. Since the beginning of the 2000s, an important research effort has been made to study different varieties of African wild fruits. In Senegal, studies have shown the nutritional potential of fruits of plant species such as baobab (*Adansonia digitata*) [2,3], bissap (*Hibiscus sabdariffa*) [4,5], and ditax (*Detarium senegalense*) [6]. These fruits are very popular in African gastronomy, and fit into the formulations of different food products put on the market by local processors. The objective of these research works is to improve the overall quality of the products and, consequently, their access to the international market. This is the case for the cactus pear (*Opuntia* spp.), which is a desert plant native of Mexico present in the northern part of Senegal (region of Saint-Louis in the north of Senegal) and is characterized by a high content of betalains [7].

Betalains are derivatives of betalamic acid that include two structural subgroups: red-violet betacyanins and yellow-orange betaxanthins [8]. They are commonly used in the food industry as an additive in many types of foods, such as dairy products, candies, jelly beans, non-alcoholic beverages, and some emulsified types of meat products [9,10]. Commercially, betalains are extracted from beetroot and are used as a red colorant, and their E number is E162. In addition to their tinctorial properties, different studies reported health-related properties associated with their consumption. They have antioxidant [11,12], antiproliferative [13,14], cardioprotective [15], and anti-inflammatory effects [16]. In the case of cactus pear juice, temperature is among the major factors affecting the stability of natural colorants in foods, together with pH, water activity, oxygen level, and light, during processing and storage. The stability of betalains is highly affected by temperature and light during processing, whereas they are generally stable in refrigerated storage [17]. A higher recovery of betaxanthins (88.5–96.8%) than betacyanins (70.9–72.4%) was reported after spray drying the cactus pear juice; the authors assumed that it was possibly due to its higher stability at high temperatures [18]. Moreover, the stability of betalain-rich extract from beetroot was evaluated when subjected to different thermal and non-thermal processes. A significant reduction in the betalain content was reported in boiled (up to 51% and 33% of betacyanin and betaxanthin, respectively) and roasted samples (up to 35% of betacyanin), whereas an increase in betaxanthin content was observed after microwaving (up to 20%) [12]. This thermal degradation has an impact on the color of the product. Herbach et al. [19] noted a shift from red-purple hues of red beet juice after thermal treatment (85 °C for up to 8 h) to yellow-orange ones. The authors proposed a mechanism that involves bond cleavage, decarboxylation, isomerization, and dehydrogenation.

In West African countries, processing is carried out mostly by small and medium enterprises (SMEs), resulting in several products, namely: concentrates, powders, and jams. However, during storage, fermentation of products can occur even in pasteurized products, showing a weak thermal inhibition of the microbial and enzyme activity. Those SMEs, because of the lack of adequate equipment and good hygiene practices, generally over-pasteurize their products in order to ensure a long shelf-life. This results in products with a very low nutritional quality, because the main nutrients, such as vitamin C, are not thermo-resistant. Although some studies have reported that the thermal degradation of betacyanins follows first-order reaction kinetics [1,20–22], they have not provided temperature/time combinations that allow for the safety of the product together with the minimum degradation of the bioactive compounds, such as betacyanin. To do so, the temperature dependency of the kinetic parameter must be established using well-known models, for example, the Arrhenius model, which is an empirical collision model based on the classic approach used for chemical reactions. It is considered the reference for modeling simple chemical reactions such as vitamin degradation, even if more concerns are raised regarding its reliability [23,24]. Other models can also be used to describe the temperature dependence, such as the theoretical Eyring model, also known as the Eyring–Polanyi model, which is based on the transition state theory in which the enthalpy of activation and the entropy of activation are the model's parameters. The Ball model follows the approach commonly used in food processing for microorganisms destruction. It defines a decimal reduction time, which is related to temperature via a z factor.

A previous paper dealt with the application of a process coupling crossflow micro- and ultra-, or nano-filtration to separate the betacyanins in Senegalese Cactus pear juice [25]. This study aims to compare the ability of classical empirical approaches (Arrhenius and Ball models), as well as an approach based on statistical thermodynamics (Eyring), to describe the thermal degradation kinetics of betacyanin in *Opuntia dillenii* Haw juice. Time/temperature combinations that allow for product safety together with minimum degradation of the betacyanins will be determined. Lastly, the impact of storage conditions on the color of the product will be monitored.

2. Materials and Methods

2.1. Plant Materials and Juice Preparation

Cactus pear fruits (*Opuntia dillenii* Haw.) were collected in August 2019 in Saint-Louis (north region of Senegal). The collected fruits were sorted, and only the fully ripe red-purple ones were kept; they were disinfected in 10 ppm of aqueous hypochlorous acid solution, rinsed with clean water, peeled, and the obtained pulps were homogenized using a Multiquick 7 electric mixer (Braun, Germany) and then filtered through a sieve to separate the seeds and obtain the corresponding juice. After this, the samples were stored at $-18\text{ }^{\circ}\text{C}$ for one month at most, before the start of the experiment.

2.2. Quantification of Betacyanin

The total betacyanins were measured according to Cassano et al. [26]. Cactus juice (2 mL) was centrifuged, then 0.5 g of supernatant was taken and diluted to 1/100th with distilled water in order to obtain absorption values between $0.8 \leq A \leq 1.0$. A portion of the juice was put in the cuvette of the spectrophotometer so as to proceed to the quantification of betacyanin. All of the analyses were carried out in triplicate. The betacyanin content (C), expressed as mg/L, was calculated using the Beer–Lambert equation (Equation (1)):

$$C = \frac{A \times DF \times MW \times 1000}{\epsilon \times L} \quad (1)$$

A is the absorption at $\lambda = 538\text{ nm}$ for betacyanins, DF is the dilution factor, and L the path-length of the 1-cm cuvette. $MW = 550\text{ g/mol}$ is the molecular weight and $\epsilon = 60,000\text{ L/mol}$ the extinction coefficient of betanin taken as a reference [27].

2.3. Measurement of the Browning of the Juice

The browning was monitored by a Specord S600 spectrophotometer (Analytik Jena AG, Jena, Germany) coupled to an F250 cryostat (Julabo, Germany). The samples were diluted in a 1/100th distilled water solution. The measurements were carried out in quartz cuvette thermostatically controlled at $25\text{ }^{\circ}\text{C}$. For each sample, the UV-VIS spectrum was recorded between 190 and 800 nm. The brown index (BI) was determined in the samples according to Equation (2) [5,28].

$$BI = \frac{A_{420}}{A_{520}} \quad (2)$$

A is the absorption at $\lambda = 420$ and 520 .

2.4. Impact of Heat Treatment on Betacyanin Degradation

The degradation of the betacyanins of cactus pear was evaluated in the samples heated at the following temperatures 60, 70, 80, and $90\text{ }^{\circ}\text{C}$. Pyrex tubes with screw caps measuring 10 cm long, 16 mm internal diameter, and 2 mm thick were used. The tubes were immersed in a thermostatically controlled water bath (WNE 7, Memmert, Schwabach, Germany). They were completely filled with prickly pear juice in order to prevent the presence of oxygen, which is known to influence the degradation of pigments. A Heidolph EKT 3001 (Heidolph Instruments, Schwabach, Germany) digital temperature controller ($\pm 1\text{ }^{\circ}\text{C}$), fitted to a filed sealed tube, was used to control the temperature during the heat treatment. The time required to reach the set temperatures and to cool the product to $10\text{ }^{\circ}\text{C}$ after heat treatment was 20 and 200 s, respectively. These very short times meant that the various heat treatments were almost isothermal. During the 60 min heat treatment, the tubes were taken every 10 min and immediately cooled in a melting ice bath at $0\text{ }^{\circ}\text{C}$. The experiment was performed in triplicate for each time/temperature combination. Samples were analyzed for betacyanin content and brown index.

2.5. Impact of Storage Temperature on Betacyanin Degradation and Color Evolution

Pyrex tubes filled with cactus pear juice were subjected to pasteurization in the same thermostatically controlled water bath at 70 °C for 30 min. This time/temperature combination corresponds to what is widely used by local small-scale processors in Senegal. After heat treatment, the tubes were cooled rapidly and then stored in absence of light 4, 25, 30, 35, and 45 °C. The samples were analyzed for betacyanin content, color, color intensity, and brown index every 10 days for 50 days. All of the samples and measurements were carried out in triplicate.

2.6. Modelling Kinetics of Betacyanin Degradation

The kinetic of betacyanin degradation was assumed as a first-order reaction. That means that the degradation rate of betacyanins is proportional to the concentration of betacyanin given by the following equation:

$$\frac{dC}{dt} = -kC \quad (3)$$

k is the rate constant of the reaction (s^{-1}).

The analytical solution of this ordinary differential equation is given by Equation (4)

$$C = C_0 \times e^{(-kt)} \quad (4)$$

C_0 represents the initial betacyanin content, C is the betacyanin content as a function of the time, and t is the time (s). To describe the temperature dependency, the Arrhenius and Eyring–Polanyi models were used, and the rate constant, k , is then expressed by Equations (5) and (6), respectively.

$$k = k_{ref} \times e^{-\frac{E_a}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right)} \quad (5)$$

k_{ref} , E_a , and R are the rate constant at the reference temperature (T_{ref}), the apparent activation energy (J/mol) for the rate constant, and the gas constant ($8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), respectively. The reference temperature was chosen in the temperature range of $T_{ref} = 363.15 \text{ K}$.

$$k = \frac{k_b}{h} T \times e^{-\frac{\Delta G^*}{RT}} = \frac{k_b}{h} T \times e^{-\frac{\Delta H^* - T\Delta S^*}{RT}} \quad (6)$$

T is the temperature expressed in K, ΔG^* is the free activation enthalpy (J/mol), ΔH^* the activation enthalpy (J/mol), ΔS^* the activation entropy (J/mol K), $k_b = \text{Boltzmann constant} = 1.381 \times 10^{-23} \text{ J/K}$, h is the Planck constant = $6.626 \times 10^{-34} \text{ J/s}$, and R is the gas constant = 8.31 J/mol K . In the case of the Ball–Bigelow model, the betacyanin content can be expressed by Equation (7):

$$C = C_0 \times 10^{-\frac{t}{D}} \quad (7)$$

D is the decimal reduction time (s) that can be expressed as a function of temperature, by the following equation:

$$D = D_0 \times 10^{-\frac{T - T_{ref}}{z}} \quad (8)$$

D_0 is the decimal reduction time (s) when $T = T_{ref}$, z is the elevation of the temperature corresponding to a decrease of D by a factor 10, expressed in °C. For this model, $T_{ref} = 70 \text{ °C}$ is commonly used for the pasteurization process.

The parameters for each model were identified by nonlinear regression with a least-square minimization procedure using the complement Excel “Solver”. This procedure allows for a more accurate identification of the constants compared with the usual logarithm linearization [29]. The uncertainty and the correlation matrix of the parameters were obtained by the VBE Macro “SolverAid” [30].

2.7. Calculation of the Optimal Time/Temperature Combination

For the isothermal treatment, the pasteurization values of $F_{70^{\circ}\text{C}}$ were calculated using Equation (9), with 70°C being chosen as the reference temperature and *Enterococcus faecalis* as the reference microorganism because of its strong heat resistance in a vegetative state, with its $D_{70^{\circ}\text{C}}$ and z factor being 2.95 min and 10°C , respectively [31].

$$F_{70^{\circ}\text{C}} = 10^{\frac{T-70}{z}} \times t \quad (9)$$

The optimum of the time/temperature combination must agree with the following two conditions: the pasteurization value must reach a minimum 10-decimal reduction of *Enterococcus faecalis* together with a maximum 10% degradation of the initial betacyanin content. These conditions are expressed mathematically by Equations (10) and (11).

$$t_{\text{pasteurization}} \geq \frac{n \times D_{70^{\circ}\text{C}}}{10^{\frac{T_{\text{pasteurization}}-70}{10}}} \quad (10)$$

n is equal to 10, corresponding to the number of decimal reductions of *Enterococcus faecalis*

$$t_{\text{pasteurization}} \leq \frac{n \times D_0}{10^{\frac{T_{\text{pasteurization}}-70}{z}}} \quad (11)$$

n is equal to 0.1, corresponding to a 10% reduction of the initial betacyanin content, and D_0 and z are the parameters estimated from the Ball model.

3. Results and Discussion

3.1. Kinetics of Betacyanins Degradation and Model Validation

The composition of the cactus pear juice from the north of Senegal was determined in a previous study [25]. The results summarized in Table 1 show a large proportion of glucose, fructose, and citric acid in the raw juice. Reduced sugars accounted for 70% of the total dry matter and citric acid accounted for 19%, which explains the very acid character of the juice. The juice was also characterized by an intense red color because of the presence of betacyanins. The attained concentrations were similar to those presented by many other studies [1]. Tamba et al. [25] performed an HPLC analysis and the three main betacyanins identified in the juice were betanin, isobetanin, and neobetanin.

Table 1. Main characteristics of raw cactus pear juice from Tamba et al. [25].

Composition	Raw Juice
Total dry matter ($\text{g}\cdot\text{kg}^{-1}$)	65.6 (0.5)
Total soluble solids ($\text{g}\cdot\text{kg}^{-1}$)	72 (1)
pH	3.35 (0.05)
Citric acid ($\text{g}\cdot\text{kg}^{-1}$)	12.4 (0.4)
Glucose ($\text{g}\cdot\text{kg}^{-1}$)	22.8 (0.1)
Fructose ($\text{g}\cdot\text{kg}^{-1}$)	22.8 (0.2)
Betacyanins ($\text{g}\cdot\text{kg}^{-1}$)	0.76 (0.02)
Turbidity (TU)	1428 (37)
Conductivity ($\text{mS}\cdot\text{cm}^{-1}$)	3.72 (0.22)
L	8.89 (0.17)
a	16.5 (0.4)
b	−1.8 (0.1)

The degradation kinetics of the betacyanins from the cactus pear juice using the Ball model is presented in Figure 1. It appears that the final betacyanin content in the juice after a 1-h-heat-treatment decreased by 6, 8, 20, and 27% at 60, 70, 80, and 90°C , respectively. Temperature therefore appears to have an impact on the degradation of

betacyanins. These results are coherent with Güneşer [20], who reported a 13 and 15% degradation of betanin in milk after 1-h at 70 and 80 °C, respectively, and 13% degradation after 30 min at 90 °C. Only the Ball model was presented, because the three models fit approximately in the same extent to the experimental values, and the graphical representation of the residual plots were the same and presented no particular trend in the data. The hypothesis of a first-order kinetic seems to be consistent. These results are confirmed by the values of the isothermal kinetic parameters corresponding to the three models of Arrhenius, Eyring, and Ball and are presented in Table 2. Firstly, the fitting of the models was almost the same, with the values of the sum of square error (SSE) being 0.0964, 0.0964, and 0.0974 for the Arrhenius, Eyring, and Ball models, respectively. This is in line with Cissé et al. [32], who found great proximity between values of R^2 at 0.988, 0.987, and 0.986 for the same three models, respectively. This can be explained by the fact that all three functions are double exponential. Secondly, for the Arrhenius model, the k_{ref} value was $1.01 \times 10^{-4} \text{ s}^{-1}$ and E_a was 56.12 kJ/mol; this means that within the temperature range of 60–90 °C, k varies from 1.88×10^{-5} to $1.01 \times 10^{-4} \text{ s}^{-1}$. These results are slightly different from those of Güneşer [20], who found k varying from 2.26 to $5.16 \times 10^{-5} \text{ s}^{-1}$ when the temperature varied from 70 to 90 °C. This difference can be attributed to the fact that they used pure molecules for betacyanin, whereas in this study, natural extracts with a more complex composition were investigated. Moreover, Merin et al. [33] found the same range for k when investigating the betacyanin degradation during the heat treatment of diluted and concentrated extracts of cactus pear between 50 and 90 °C. However, the authors found E_a values significantly lower between 7 and 10 kJ/mol. Herbach et al. [19] reported a value of k equal to $7.67 \times 10^{-5} \text{ s}^{-1}$ for betacyanin degradation when heating pitaya juice at 85 °C, and Fernández-López et al. found k equal to $2.77 \times 10^{-5} \text{ s}^{-1}$ and $2.51 \times 10^{-4} \text{ s}^{-1}$ at 50 °C and 90 °C, respectively, in solutions of natural red pigment extracts of *Opuntia* fruits. The E_a value found in this last study was 53.31 kJ/mol. The parameters estimated by the Eyring and the Ball model were in the same range as those reported for anthocyanins in roselle extract [32].

Table 2. Parameters for the thermal degradation of anthocyanins, following different models.

Model	Parameters	Estimate (CI 95%)	Correlation Matrix		SSE
Arrhenius	E_a (kJ/mol)	56.12 (8.26)	E_a	k_{ref}	0.0964
	$k_{ref} \times 10^{-4}$ (s ⁻¹)	1.01 (0.08)	1	-1	
Eyring	ΔH^* (kJ/mol)	53.20 (9.80)	ΔH^*	ΔS^*	0.0964
	ΔS^* (J/mol)	176.42 (27.84)	1	0.999	
Ball	z (°C)	42.21 (6.23)	z	D	0.0974
	$D \times 10^4$ (s)	6.79 (0.892)	1	-0.859	
			-0.859	1	

Among the models, despite their proximity in terms of precision, it appears that the Ball model is more relevant and should be used to make predictions. Indeed, the analysis of the correlation matrix showed a strong correlation between the estimated parameters of the Arrhenius and Ball models of -1 and 0.999, respectively, whereas it was lower for the Ball model at -0.859. Although widely used in the literature, many studies have recently criticized the Arrhenius model because of the necessity for researchers to define “energy of activation”, which has no relevant meaning in food reactions [23]. Moreover, in the case of the Eyring equation, a recent study showed that in most cases, the entropy–enthalpy ($\Delta H - T\Delta S$) compensation is meaningless because of the large correlated errors in ΔH and $T\Delta S$, unless special measures are taken to minimize, quantify, and propagate these errors [34]. Given these observations, from this point in the article, the Ball equation will be used to make the simulations.

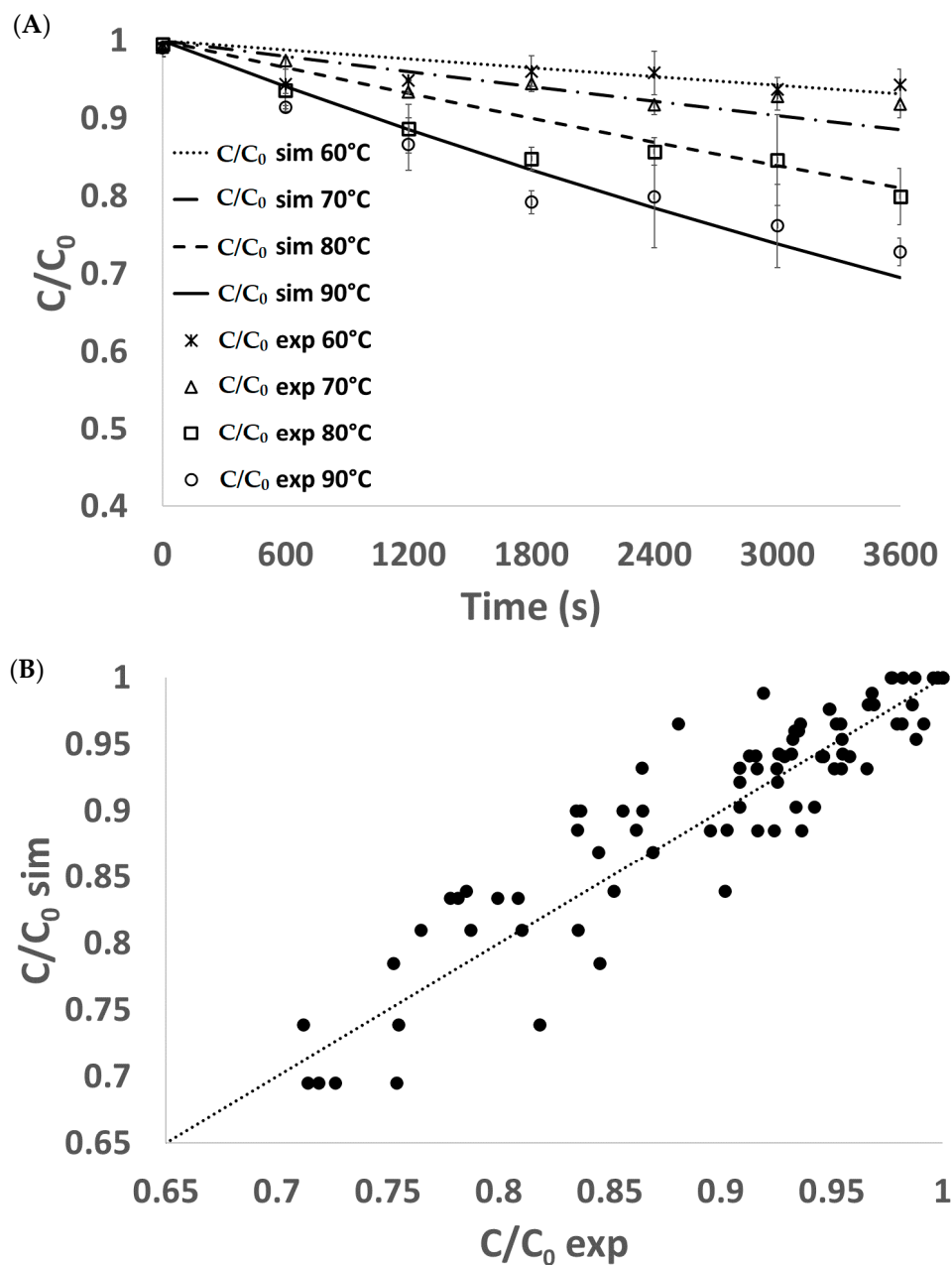


Figure 1. Time course of intrinsic betacyanin (C/C_0) heated at different temperatures (A). Solid lines represent the fit of the Ball model (C/C_0 sim), while experimental data (C/C_0 exp) are represented by symbols ($*$), (\circ), (\square), (\triangle). Residual plots from the experimental and simulated data (B).

3.2. Model Predictions of Time/Temperature Combinations

Under isothermal conditions for a given value at different setup temperatures, betacyanin losses estimated by the Ball model are plotted in Figure 2. It appears that lower $F_{70^\circ\text{C}}$ values significantly preserve betacyanin. In addition, for the same $F_{70^\circ\text{C}}$ value, betacyanin loss decreased with an increasing temperature. This is consistent with the fact that pasteurization with high-temperature short time conditions (HTST) generally preserve a bioactive compound. Classic pasteurization does not significantly damage betacyanin. Indeed, for $F_{70^\circ\text{C}}$ values between 100 and 200 min, which are typically used for the thermal treatment of fruit beverages, temperatures above 80 °C maintained the loss of betacyanins at below 10% by the end of the process. The same results were found in blackberry (*R. adenotrichus* Schlech) and roselle (*H. sabdariffa* L.) juice [32]. This result is very important, because

it shows that betacyanins resist typical heat treatment conditions. This is confirmed by Figure 3, which shows the time/temperature combinations that can ensure the safety of the product together with the minimum degradation of the betacyanins (10%). With *Enterococcus faecalis* as the reference microorganism, it appears that for a maximum temperature of 100 °C, the pasteurization time satisfying these two conditions is 0.6 min, whereas when the temperature is 62 °C, the pasteurization time becomes 180 min. The typical pasteurization conditions used by small-scale processors correspond to 75 °C for 30 min, and although it is severe, it agrees with the two constraints and should lead to safe products with good nutritional qualities. The results of these two figures also confirm the benefit of using high-temperature short time conditions (HTST) to preserve bioactive molecules in food products. They are in line with the results reported for anthocyanins showing the same degradation for the same $F_{70^{\circ}\text{C}}$ values in roselle juice [32].

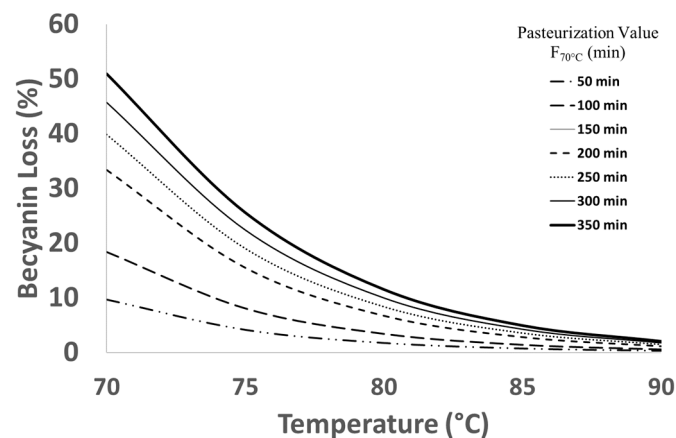


Figure 2. Estimated betacyanin losses during isothermal treatments of cactus pear juice with varied setup temperatures and different $F_{70^{\circ}\text{C}}$ values using the Ball model.

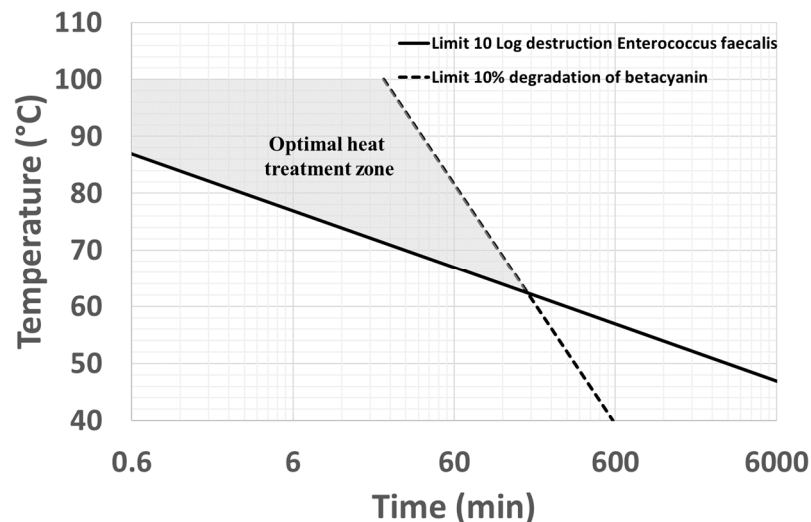


Figure 3. Representation of the evolution of the temperature of pasteurization as a function of pasteurization time. The grey zone represents the time/temperature combination that ensures both a maximum 10% reduction and a minimum 10 log reduction for *Enterococcus faecalis*.

3.3. Impact of the Storage Temperature on the Degradation of Betacyanin and the Browning of Cactus Pear Juice

The impact of the storage temperature was evaluated on samples of cactus pear juice pasteurized at 70 °C for 30 min. The changes in the betacyanin contents and the chromatic characteristics of the products were monitored for 50 days. We noted that over time,

the betacyanins degraded regardless of the temperature. However, the intensity of the degradation is positively correlated with the storage temperature of the juice. Figure 4 shows that a higher loss of betacyanin was found at 35 and 45 °C, corresponding to 53% and 65%, respectively, after 50 days of storage. We noted that when stored at 4 °C, only 18% of the betacyanins present in the juice were degraded after 50 days. These results are in line with those of Caldas-Cueva et al. [35], who showed that temperature during storage affects the stability of betalains, by comparing betacyanin-rich extracts from ayrampo (*Opuntia soehrensii* Britton and Rose) and beetroot at refrigerated conditions (4 °C), room temperature (25 °C) and high temperature (80 °C). The fluctuation of betacyanin content at 45 °C after a storage of 40 days seems to be caused by experimental bias. The fact that the betacyanin content was lower after 40 days than after 50 days of storage is hard to explain scientifically, and to the best of our knowledge, no study reported this particular trend in the literature.

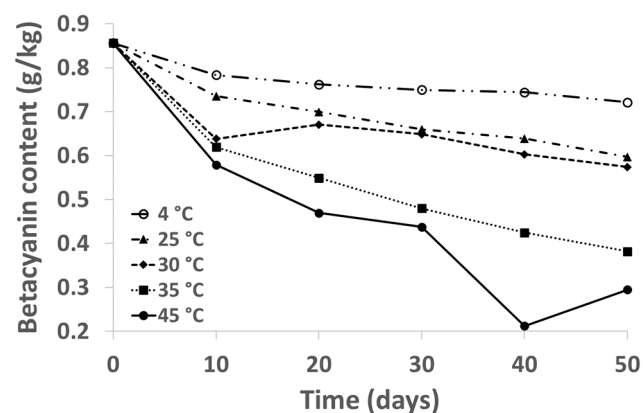


Figure 4. Evolution of the betacyanin content of samples of cactus pear juice at different temperatures during storage in the dark.

The degradation of betalains can occur from different reactions, such as isomerization, deglycosylation, dehydrogenation, and hydrolysis, which will result in a gradual reduction of the red color and in the appearance of a brown shade [12]. The browning index is a parameter assessing the quality of the color of a food matrix. It represents the proportion of the color yellow on red. As a result, the higher the index, the more the product turns brown. We note in Figure 5 that the browning of the juice is correlated with an increase in the temperature and storage time. At 45 °C, this parameter was two times higher than at 4 °C after 50 days of storage, with a maximum of 0.62. This trend was reported in the case of anthocyanins by previous studies. Sinela et al. [5] showed that the brown index increased during storage. At 37 °C, this parameter was three times higher than at 4 °C after 60 days, and Cisse et al., 2012 [4], found that the thermal degradation of anthocyanins in roselle extracts led to a red color loss and to the subsequent formation of a brown color. The authors assumed that the large increase in brown index values and the corresponding loss of monomeric anthocyanin with storage in all thermally processed products may be due to the products of anthocyanin degradation, such as protocatechuic acid and gallic acid, but also the copigmentation of anthocyanins. Identical reactions may happen in the case of betacyanin.

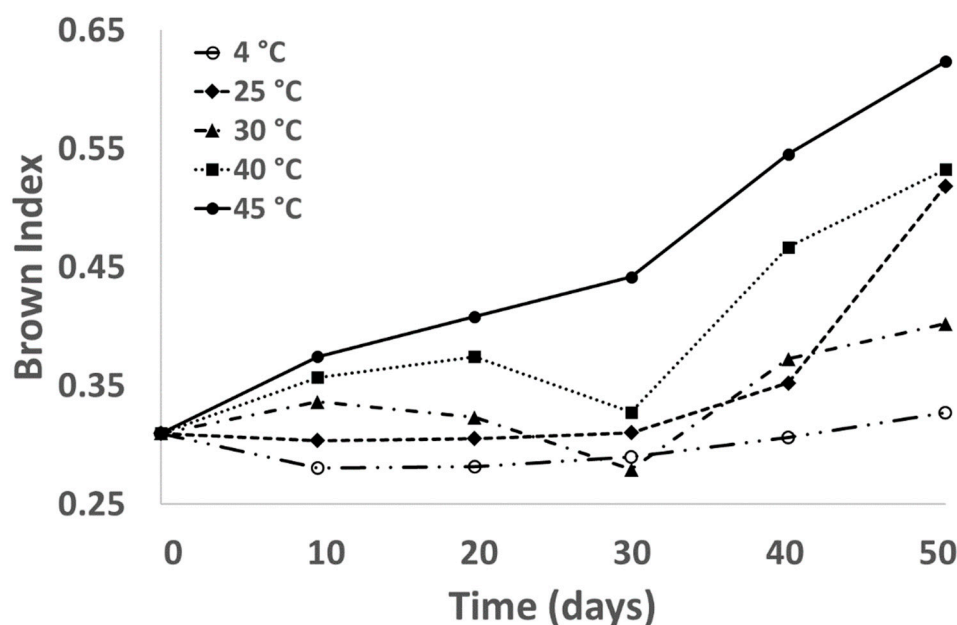


Figure 5. Evolution of the brown index during storage in the dark of samples of cactus pear juice at different temperatures.

4. Conclusions

Our study evaluated the impact of temperature (60–90 °C) on betacyanin degradation in cactus pear juice. The data show that the thermal degradation of betacyanins can be described using first-order reaction kinetics. The Ball equation is more suited to describe the variation in the betacyanins content because the model leads to less correlated parameters in comparison with the Arrhenius or Eyring equations. The Ball model could easily be used as a tool to predict time/temperature combinations, which can assure both the safety of the product and the preservation of betacyanins. The degradation of betacyanins during storage is positively correlated with temperature, and is accompanied by the appearance of a brown shade. In industry, pasteurization at a temperature of 90 °C for 36 s should be enough to ensure both the quality and safety of the end product. Concerning storage, temperatures under 20 °C should be prioritized to ensure the stability of the product for at least 2 months. This study focused on the thermal degradation of betacyanins, however more investigation must be done on other betalain compounds in order to have a global understanding of the phenomena taking place in the food matrix. Moreover, the impact of other parameters such as pH, oxygen, or light on the kinetic of betalain degradation must be investigated further.

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