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Optimization, Quality and Shelf-Life Analysis of Jam Production from Blended Cactus Pear (*Opuntia Ficus-Indica*) and Strawberry (*Fragaria*) Fruits

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Abstract

The cactus pear (*Opuntia ficus-indica*) is a resilient, nutritious fruit suitable for sustainable food development in semi-arid regions, but faces postharvest challenges like short shelf-life. This study aimed to optimize and analyze jam made from blending cactus pear with strawberry (*Fragaria*). Using response surface methodology (RSM) coupled with central composite rotatable design (CCRD), the optimal processing conditions were determined as a cooking temperature of 90 °C, time of 20 minutes, and blending ratio of 16.9%. The blended fruit jam produced at the above-mentioned optimum values of processing showed a titratable acidity (TA) of 1.9 ±0.12% citric acid, 58.6

± 0.72 °Brix of total soluble solids (TSS), 6.8 ± 0.51 mg/100g citric acid of vitamin C (Vit C), and 3.2 ± 0.3 of pH value. The total plate count and yeast and molds of the final jam were recorded as 2.6 ± 0.15 (CFU)/g and < 1 (CFU)/g respectively. Shelf life qualities (titratable acidity, total soluble solids, vitamin C, total plate count and yeast and molds) of the produced jam investigated after nine months storage showed slight change. Based on the vitamin C degradation kinetics, the developed first order kinetic model with $R^2 = 0.99168$ demonstrated superior shelf life prediction capacity for the produced jam. Hence, a better food value chain could be produced from the perishable cactus pear fruit by developing a jam.

KEYWORDS: Cactus-pear fruit, optimization, blending, jam qualities, shelf-life

1. Introduction

The cactus pear fruit is a small, round, fleshy with an inferior ovary that has very good chemical compositions. The fruit is rich in essential nutrients, including vitamins, minerals, and antioxidants, making it a valuable component of a healthy diet. Mainly, it is rich in biochemical, fatty acid profiles, organic acid, mineral compositions, and antioxidant activities (Tunç et al., 2025). Cactus pear fruit contained 33–55% peel and the remaining accounts for pulp and seed (De Wit et al., 2020). It has promising contents of polyphenols, ascorbic acid, and sugars. In particular, the ripened orange cactus pear has lutein (0.0044 mg/100 g), lycopene (0.069 mg/100 g), and β -carotene (0.025 mg/100 g) (Yahia and Sáenz, 2011). Besides, orange type of cactus pear fruit contains 326.4 mg.L^{-1} (equivalent to gallic acid) total phenol, 0.92 mg.mL^{-1} tartaric acid, 0.16 mg.mL^{-1} citric acid and 0.02 mg.mL^{-1} ascorbic acid (Tsegay and Gebremedhin, 2019). The amount of ascorbic acid in the fruit is considerably relative to other common fruits, such as apples, grapes, and bananas (Yahia and Mondragon-Jacobo, 2011). Orange-type cactus pear fruit contain important nutritional components that make it a

promising ingredient for developing functional foods like jam, particularly when blended with other fruits. However, despite its potential, cactus pear value chains are often underdeveloped and face challenges due to post-harvest losses, limited commercial product development, inadequate processing infrastructure, and restricted market access.

Jams are a type of functional food product with a total soluble solid content of greater than 45 °Brix and consist of at least 45% fruit content. Moreover, fruit jams are prepared from fruit (pieces, juice or pulp), sugar, pectin, and citric acid; are normally canned or sealed for long-term storage; and are commonly used with breads, cookies, and cake fillings, among others (Koç Alibaşoğlu et al., 2024; Mohd Naeem et al., 2017; Morelli and Prado, 2012).

Presence of pectin, sugar, citric and tartaric acid content is determining factor for viscosity of the pulp during the production of juices, marmalades and jams. Specifically, pectin content in the cactus pear pulp (0.17-0.21%) is not sufficient to produce gels property of the final jam (Terki et al., 2025). Adding pectin sources, sugar, and citric acid during jam cooking is mandatory for controlling texture and preservation. Pectin sources and sugar are added for gelling, while citric acid is used for both gelatinization and adjusting the pH (Veliu et al., 2025). Studies have shown the production of jelly and jams from cactus pear fruit (Akelom et al., 2022; Saenz, 2000; Sawaya et al., 1983). Sawaya et al. (1983) investigated cactus pear fruit jam manufacturing using blanching, a pulp-to-sugar ratio of 60:40, 1.25% pectin, and citric acid or a 1:1 mix of citric and tartaric acids. Jam produced with good sensory quality and microbiological stability from cladodes, sugar and citric acid in the proportion of 1:0.6:0.01. Moreover, jam produced from cladodes (cactus stems or pads) by adding orange juice, orange peel, and sugar to the ratio 1:1.5:0.8:0.08 has shown no microbial growth after 40 days of storage as reported by Saenz (2000).

The blending of strawberry with cactus pear in this study was intended to incorporate the strawberry's important flavoring and coloring components into the jam. Furthermore, the nutritional content of strawberry is sufficient for jam production and can improve the flavor of other fruit jams (Holzwarth et al., 2013; Levaj et al., 2012; Watanabe et al., 2011). Physical and sensory qualities of strawberry fruits are associated with traits like size, firmness, colour, pH, sugar/acid ratio, taste and aroma. Specifically, fruit jam produced from fully ripe strawberry fruit has shown chemical composition stability during storage at 4 and 20 °C for 3 and 6 months (Mazur et al., 2014). These important properties of the strawberry fruit are ones that could help to enhance the physicochemical properties and sensorial acceptance to produce cactus pear fruit jam.

While global cactus pear production offers sustainable food chain opportunities, much of the fruit in Tigray, Ethiopia, is wasted due to limited industrial processing. Inadequate knowledge and technical capacity currently hinder cactus pear fruit product development and distribution. The blending of cactus pear fruit with strawberry fruit to develop jam and improve its quality is scarcely studied. Moreover, optimizing jam processing factors such as temperature, time, and blending ratios with other fruits is essential to demonstrate the quality of cactus pear fruit jams. Hence, developing a predictable model for blended jam processing to ensure acceptable chemical and microbial qualities, along with a prolonged shelf life, is fundamental to high-quality jam production. This study aimed to optimize jam processing variables, analyze chemical and microbial qualities, and predict the shelf life of a jam blend produced from cactus pear (*Opuntia ficus-indica*) and strawberry (*Fragaria*).

2. Materials and methods

2.1. Chemicals and reagents

Sodium iodide, sodium iodate, sodium hydroxide, starch, phenolphthalein solution, pH 4 and 7 buffer solutions, yeast extract, D-glucose, Plate count agar (PCA), sulphuric acid, and L-ascorbic acid were from Loba-Chemie Laboratory Reagents and Fine Chemicals Co. India, Mumbai, India. These chemicals and reagents were analytical grade and procured from multiple commercial vendors (Addis Ababa, Ethiopia).

2.2. Raw materials collection and preparation

Orange color type (mature and healthy) of raw cactus pear fruit (*Opuntia ficus-indica*) varieties (depicted in Figure 1) were harvested during September 2024, from Kerseber around Adigrat city, Eastern Tigray, Northern part of Ethiopia. Fresh strawberries (Monterey variety) were collected from Raya Horti Farm Enterprise Raya, Southern Tigray, Northern part of Ethiopia during September 2024. Both fruit samples were selected at their maturity standard and preserved below 0 °C using an ice box during transportation.

Experimental data were collected for the preliminary characterization, optimization, and confirmation of the fresh juice and jam. The shelf-life of the cactus pear and strawberry blended jam produced at the optimum values was then predicted based on vitamin C degradation during one, two, three, six, and nine months storage at room-temperature (25 °C). The general processing flowchart is shown in Figure 1.

acidity of the extracted individual juices were measured before jam processing to check its suitability.

These input factors were applied to optimize the total soluble solids, vitamin C (ascorbic acid) content, and total titratable acidity of the blended fruit jam. A Central Composite Rotatable Design (CCRD) was employed, comprising 6 axial points ($\pm\alpha$), 6 center points (0), and 8 factorial points (± 1). The CCRD based on the three input parameters is shown in Table 1. Based on this experimental design, 20 randomized experimental runs were conducted (Table 2), and the results were recorded for each response.

The experimental results were tested to fit a polynomial model (Equation 1). The appropriate model was tested using linear, two-factor-interaction, or quadratic functions. The polynomial function was also employed to determine critical points (maximum, minimum, or saddle) and to understand the impacts of independent jam-making variables on the predicted responses (Montgomery, 2017). Finally, the chemical and microbial characteristics of the prepared blended fruit jam developed at the optimum values were analyzed.

$$3. Y = \beta_0 + \sum_{i=1}^3 \beta_i x_i + \sum_{i=1}^3 \beta_{ii} x_i^2 + \sum_{i=1}^3 \sum_{j=(i+1)}^3 \beta_{ij} x_i x_j \quad (1)$$

Where Y stands for total titratable acidity (TA in % Citric acid), total soluble solids (TSS in °Brix), and vitamin C (mg/100g) to be predicted; i, j represents

linear, quadratic coefficients, correspondingly. x_i and x_j correspond to the three independent variables (cooking temperature, cooking time and ratio of strawberry fruit juice), b_0 (intercept), b_i (linear effects), b_{ii} (squared effects) and b_{ij} (interaction terms) were for regression coefficients.

Table 1: CCRD of independent variable values and their corresponding factor levels

Independent processing variable	Symbols	Factor levels				
		$-\alpha$	-1	0	+1	$+\alpha$
Blending ratio (% w/w)	A	6.5	10	15	20	23.4
Temperature (°C)	B	63	70	80	90	97

Time (minute) C 13.3 15 17.5 20 22

Adequacy of the developed models to predict the actual responses (quality) of the produced jam were criticized with respect to ‘‘lack of fit’’ test and 95% confidence level. Moreover, regression coefficients in the model (R^2), adjusted regression coefficient (adj- R^2), Predicted R^2 (pre- R^2), Adeq. Precision, and Coefficient of variation (C.V) were employed for each model adequacy test employing the Design-Expert software version 10.1.

Table 2: Experimental design, average values of triplicate measured results, and expected outputs for the blended jam product of cactus pear and strawberry fruits.

Standard ordered	Controlled factors			Responses					
	Temp. (°C)	Time (min)	Blending ratio (%)	TA (% Acid)		TSS (°Brix)		Vit C (mg/100g)	
				Predicted value	Measured value	Predicted value	Measured value	Predicted value	Measured value
1	70	15	10	2.09	2.11	39.79	37.5	4.86	5.3
2	90	15	10	2.25	2.11	44.63	44.2	5.08	4.5
3	70	20	10	2.09	2.1	52.49	55.9	4.89	4.5
4	90	20	10	2.25	2.42	57.34	54.5	6.41	6.1
5	70	15	20	2.38	2.31	39.19	36.1	5.83	5.7
6	90	15	20	2.54	2.35	57.79	54.3	6.05	6.5
7	70	20	20	2.38	2.31	39.45	39.8	4.77	4.9
8	90	20	20	2.54	2.97	58.05	54.4	6.29	5.3
9	63	17.5	15	2.18	2.31	38.63	35.9	4.62	4.5
10	97	17.5	15	2.45	2.34	58.55	61	6.11	6.5
11	80	13.3	15	2.32	2.31	43.15	47.9	5.52	5.3
12	80	22	15	2.32	2.11	54.42	55.2	5.67	6.1
13	80	17.5	6.5	2.07	1.93	48.54	48.7	5.3	5.7
14	80	17.5	23.4	2.56	2.38	48.64	53.4	6.03	5.9

15	80	17.5	15	2.32	2.42	48.59	49.4	6.24	6.5
16	80	17.5	15	2.32	2.19	48.59	50.5	6.24	6.1
17	80	17.5	15	2.32	2.46	48.59	45.8	6.24	6.1
18	80	17.5	15	2.32	2.46	48.59	45.6	6.24	5.3
19	80	17.5	15	2.32	2.56	48.59	47.9	6.24	6.5
20	80	17.5	15	2.32	2.15	48.59	54.2	6.24	6.5

2.4 Juice extraction

Unripe and damaged strawberries were removed and sorted by size and color. Stems and sepals were removed, and the strawberries were washed under running tap water before draining the excess water. Cactus pears were sorted for external injuries, washed, and manually peeled. The fruit pulps were juiced using a commercial small-scale blender (Multi-Purpose Blender, Model- TYB-313, Tongyuan Hardware & Electric Co., Ltd., China), and the seeds were removed with a commercial sterilized strainer (Stainless Steel Soup & Juice Strainer/Liquid Filter (15 cm Diameter) krishna kripa, PLANET 007, India). Juice samples were stored at 5 °C for a maximum of 24 hours. The strawberries were then manually cut vertically into 4-5 slices using a sterilized stainless-steel slicer (Maritza et al., 2012; Reyes-Hernández et al., 2017). Strawberry juice was produced using commercial small-scale juice blender (Multi-Purpose Blender, Model- TYB-313, Tongyuan Hardware & Electric Co., Ltd., China). The overall strawberry and cactus pear fruit processing diagram is illustrated in Figure 1.

2.5 Jam processing

For the blended fruit jam, each blend was prepared by adding 25% table sugar, 5% citric acid (lemon juice), and 5% pectin extract (extracted from orange peel). Pre-experimental tests established the process parameters, aiming for a final product with soluble solids between 45% and 67% (Kopjar et al., 2009). After processing, the jam was cooked according to the developed

experimental run, and the finished samples were sealed in glass bottles to prevent air exposure before analysis.

2.6 Chemical and microbial analysis of the jam

2.6.1 Determination of ascorbic acid (AA)

Vitamin C was quantified using an iodometric titration, based on a modified procedure by Spínola et al. (2013) with some modifications. The 0.002 mol/L potassium iodate solution was first standardized with L-ascorbic acid. Subsequently, to the 10 mL of a standard or sample solution, 1 mL of each 10 g/L starch, 0.5 M HCl, and 100 g/L potassium iodide were added. Then, the prepared solution (standard or sample) was titrated with the standardized potassium iodate until a dark blue color persisted for at least 60 seconds.

2.6.2 Total soluble content

The total soluble solids of the individual juice and after treatment of the blended jam were measured using a digital refractometer (Benchtop Abbe Refractometer (WAY-2S, Origin China)) (Ahmed et al., 2017).

2.6.3 pH and titratable acidity

The pH of both fresh juices and the produced jam was measured using a calibrated Wisebee Digital pH Meter (Wisebee Digital pH Meter, Backlit LCD Display | Pocket-Size | 0-14 PH, Mirowise) by dissolving 50g of jam sample in 100 mL of distilled water, or by using 50 mL of juice directly (Tabakoglu and Karaca, 2018). Titratable acidity was assessed by titrating a 10 mL sample of diluted juice or jam (1:5 juice-to-water ratio) with 0.1 M NaOH, using phenolphthalein as a visual endpoint indicator. Total acidity was calculated as the citric acid equivalent (Tabakoglu and Karaca, 2018).

2.6.4 Microbial analysis

To determine the microbial count, 10 mL of jam was mixed with 90 mL of sterile peptone water. Sequential dilutions were then performed. From the appropriate dilutions, 0.1 mL was spread-plated onto Plate Count Agar (PCA) and YEPD (1% yeast extract, 2% peptone, 2% glucose) media (Ayed and Hamdi, 2015).

2.7 Shelf-life analysis of produced blended fruit juice jam

Vitamin C degradation, pH, total soluble solids, total titratable acidity, and microbial growth (total bacteria, yeast, and mold) were measured at specific intervals during storage at 25 °C. Total bacteria were quantified as total plate count (TPC) and Vitamin C was measured using iodometric titration. The standard equations for zero-order and first-order Arrhenius reaction models (Equations 5 and 7) are important to calculate the degradation kinetics for physicochemical and storage qualities of foods (Patras et al., 2011). Therefore, the shelf life of the blended fruit jam, considering the rate of Vitamin C deterioration, was estimated using the Arrhenius models presented in Equations 5 and 7 by monitoring its quality over nine months (Kim et al., 2022). Following the statistical significance of the models (residual sum of squares and predicted R^2) the best fitting reaction model was reported.

2.8 Data analysis

Response surface methodology (RSM) coupled with central composite rotatable design (CCRD) was applied using Design-Expert software (version 10.1; Stat-Ease Inc., Minneapolis, MN, USA) to investigate the overall effect of independent variables on output variables. Origin software (version 9.1; OriginLab Corporation, Northampton, MA, USA) was used for statistical correlation analysis, specifically to develop zero and first-order curves.

3. Results and Discussion

3.1. Response surface model fitting

Employing RSM coupled with a CCRD trial plan (Equation 1), experimental data were analyzed to evaluate model fit (linear, two-factor, or quadratic). As Table 3 indicates, the suggested models for the experimental responses are linear for Titratable Acidity (TA), two-factor interaction for Total Soluble Solids (TSS), and quadratic for vitamin C. A cubic model proved aliased in all responses, so the models were evaluated based on the suggested linear, two-factor, or quadratic fits.

To evaluate the fit and determine the statistical significance of the developed model terms, ANOVA and regression analyses were performed. The ANOVA for the linear and two-factor interaction analyses for TA and TSS are summarized in Table 4, while the analysis for the developed quadratic model for vitamin C is presented in Table 5. An overall summary of the Analysis of Variance (ANOVA) for all responses is compiled in Table 6.

The linear and two-factor interaction models significantly ($p < 0.05$) represented the experimental results for the titratable acidity and total soluble solids of the final fruit jam, respectively. The vitamin C content, however, was best represented by a significant quadratic polynomial model ($p < 0.05$). In all cases, the lack of fit for the developed models was found to be insignificant, as shown in Tables 4 and 5.

Three-dimensional (3D) response surface and two-dimensional (2D) contour plots were used to illustrate the effects of input factors on the responses, the relationship of the processing factors and response, and to predict the quality of the produced jam. The contour surface plotted against the combination of factors which are depicted in the bottom of the 3D response surface illustrations. As illustrated in Figures 2 and 3, the interaction effects of two cooking factors on the TSS and vitamin C properties are depicted while the third factor is held constant. The 3D response surface and contour plots were not necessary for TA, as its predicting model was linear.

In Table 3, the reported adjusted and predicted R^2 values of the developed models were determined before screening for the significant factors. After

screening significant factors, the adequacy of the models was rechecked, and their values were summarized in Table 6.

Table 3: Summary of model fit for responses before screening factors.

Type of response	Source	Sequential p-value	Lack of Fit p-value	Adjusted R ²	Predicted R ²	
TA	Linear	0.0301	0.3936	0.3102	0.0460	Suggested
	2FI	0.2485	0.4412	0.3748	-0.1823	
	Quadratic	0.6127	0.3468	0.3163	-0.9228	
	Cubic	0.3468		0.4418		Aliased
TSS	Linear	0.0007	0.1574	0.5762	0.3815	
	2FI	0.0134	0.4284	0.7648	0.4795	Suggested
	Quadratic	0.8521	0.2768	0.7164	0.2138	
	Cubic	0.2768		0.7938		Aliased
Vit C	Linear	0.0627	0.0338	0.2380	-0.0303	
	2FI	0.2410	0.0374	0.3132	-0.8428	
	Quadratic	0.0528	0.0869	0.5725	-0.5353	Suggested
	Cubic	0.0869		0.8197		Aliased

3.2. Effects of jam processing variables on quality responses

Understanding the nature of the primary fruit source, effect of fruit jam processing factors, and optimizing their effect is vital to develop a quality jam product. In the present study, we considered the effect of jam cooking temperature, time and blending ratio of strawberry fruit to produce cactus pear fruit jam. Hence, the individual and interactive effects of these input factors to predict the titratable acidity (TA), total soluble solids (TSS), and vitamin C (Vit C) of the final jam are discussed.

Cooking temperature, pH, time, and blending ingredients are main factors in fruit jam processing. High processing temperatures can deplete nutrients and vitamins. Additionally, both high processing and storage temperatures can lead to a decrease in pH, vitamin loss, total phenolics, antioxidant activity, and anthocyanins. In contrast, increasing the temperature during processing enhances the total soluble solids (TSS) of the fruit jam (Rababah et al., 2014).

For instance, increased temperature during processing reduces the pH, partly due to the formation of hydroxymethoxyfurfural (HMF), while TSS increases with temperature (Rababah et al., 2014). As reported by Rababah et al. (2014), the TSS of cherry jam increased from 11.25% to 66.22% as the temperature elevated from 25 to 55 °C. Similarly, Touati et al. (2014) reported that during apricot jam storage, increasing the temperature from 5 to 37 °C caused the pH to decrease from 3.39 to 3.21, but the titratable acidity slightly increased from 0.98% to 1.03% and TSS increased from 64.42% to 67.305%. The fact that the rise in TSS during fruit jam cooking is due to the process where increased temperature speeds up the evaporation of water, which concentrates the soluble solids (primarily sugars) and increases the TSS value (Vu et al., 2023).

Table 4: Linear and Two-Factor interaction Analysis of Variance (ANOVA) for TA and TSS, respectively.

Type of response	Source	Sum of Squares	df	Mean Square	F-value	p-value
TA	Model	0.3867	3	0.1289	3.85	0.0301**S
	A-Temp.	0.0832	1	0.0832	2.48	0.1345*
	B-Time	0.0223	1	0.0223	0.6643	0.4270
	C- Blending ratio	0.2812	1	0.2812	8.39	0.0105**
	Residual	0.5360	16	0.0335		
	Lack of Fit	0.4005	11	0.0364	1.34	0.3936
	Pure Error	0.1355	5	0.0271		
TSS	Model	810.16	6	135.03	11.29	0.0002**
	A-Temp.	473.42	1	473.42	39.60	< 0.0001**
	B-Time	147.58	1	147.58	12.34	0.0038**
	C- Blending ratio	0.0113	1	0.0113	0.0009	0.9759
	AB	17.11	1	17.11	1.43	0.2529
	AC	94.53	1	94.53	7.91	0.0147**
	BC	77.50	1	77.50	6.48	0.0244**
	Residual	155.42	13	11.96		
	Lack of Fit	103.02	8	12.88	1.23	0.4284

	Pure Error	52.40	5	10.48		
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**Model terms are significant at $p < 0.1$, *Model terms are less significant at $p < 0.2$, other values of model terms are insignificant.

3.2.1. Effect of process variables on total titratable acid (TA)

The effects of jam processing factors (temperature, time, and strawberry fruit blending) on total titratable acidity (TA) were investigated. After careful analysis of the model development using Design-Expert software version 10.1, a linear model was suggested, as the cubic model was aliased (Table 3).

As shown in Table 4, among the linear model terms, only the strawberry fruit blending ratio had a significant effect (at $p < 0.1$), while the effect of cooking temperature was less significant (at $p > 0.1$). The effect of cooking time was also found to be insignificant ($p > 0.1$).

The initial titratable acidity of the jam is directly related to the inherent organic acid content of the fruits used in the blend. In particular, gel formation in fruit jam is determined by the amount of organic acid present, which facilitates the release of pectin from fruit cells. Inadequate organic acid concentration, whether too high or too low, can result in poor gel quality. Specifically, insufficient acid prevents gel formation, while excessive acid can cause the gel to liquefy. Hence, proper gel formation can be achieved by adding ingredients like lemon juice or other acids (Bekele et al., 2020). In the present study, we used lemon juice at a constant rate, and thus the cooking effect did not vary. However, the addition of strawberry fruit significantly affected the TA of the final jam, likely due to the inherent acidity of the fruit and the amount used in the blend efficiently enhancing the jam's overall TA. This is due to the fruit pulp and sugar ratio, which influenced the effect of blending strawberries into the cactus pear fruit for jam making. From our initial characterization of the cactus pear and strawberry fruit juices (Table 8), strawberry generally has a higher initial titratable acidity

and lower pH (4.5 ± 0.25) compared to cactus pear fruit. Cactus pear fruit has a lower natural acidity (pH of 6.03 ± 0.05).

The processing temperature has little effect on the titratable acidity. This is due to the fact that titratable acidity is largely a function of the initial fruit pulp and sugar ratio (Singh et al., 2009). However, the processing temperature and time have a less significant influence on the final TA value immediately after cooking.

The less significant effect of cooking temperature is consistent with a report by Chalchisa et al. (2022), who investigated the effects of ingredient proportions and processing temperature on pineapple jam production. They reported that processing temperatures between 90°C and 105°C slightly decreased TA, potentially because increased temperatures enhanced the jam's pH value. Controlling the temperature within a specific range (approximately $104\text{--}105^{\circ}\text{C}$) enables the development of optimal gel formation in fruit jam. Therefore, to ensure proper jam setting through the pectin-sugar-acid interaction, maintaining this optimal temperature is more crucial than specifically operating the acidity level only (Bekele et al., 2020; Singh et al., 2009). Hence, further studies to optimize the interaction of specific organic acids and the pH value of the cactus pear fruit and strawberry fruit blend to predict the perfect pectin-sugar-acid interaction formation are important.

3.2.2. Effect of process variables on total soluble solids (TSS)

The total soluble solids (TSS) of the produced blended fruit jam are affected by the cooking temperature and time. However, the linear effect of the strawberry fruit blending ratio was insignificant. Based on the analysis of the experimental results, the suggested model is a two-factor interaction, in which the cubic model is aliased (Table 3).

As observed in Table 4, except for the interaction effect of cooking temperature with time ($p > 0.1$), the interaction effects of the blending ratio

with both cooking temperature and time had a significant effect (at $p < 0.1$) on the TSS of the final jam.

Figures 2A, 2B, and 2C illustrate the interaction effects of cooking temperature, time, and strawberry fruit blending ratio on the jam's TSS. The strawberry fruit blending ratio and cooking temperature simultaneously raised the TSS to about 49.985% by setting the cooking time constant at 17.5 minutes (Figure 2B). Moreover, at a constant cooking temperature (80°C), the interactive effects of the strawberry fruit blending ratio and cooking time slightly enhanced the TSS (48.958%) (Figure 2C). The interaction effect of cooking temperature and time was insignificant. Fruit jam TSS are influenced by cooking temperature, duration, and the inclusion of added ingredients, such as blended fruits. This is due to the fact that, increasing the cooking temperature over an extended period facilitates water evaporation, which concentrates the soluble solids, primarily sugars. Similarly, a larger blending ratio of fruits with high sugar content results in a higher TSS for the mixture (Vu et al., 2023).

The observed increase in TSS with increasing cooking time is consistent with the study on strawberry jam cooking reported by Okut et al. (2018). They found that at elevated fruit cooking durations, water evaporation speeds up. However, the difference in the total soluble solids (TSS) value in our fruit jam and their reported value could be due to variations in the soluble sugar and pectin content present in the initial fruit composition. The amount and type of soluble sugar and pectin present in the initial blending fruits or ingredients could influence the final jam quality (Shinwari and Rao, 2020).

Setting the proper TSS to about 63 °Brix for a jam improves texture stability, color suitability, and consumer preference (Vu et al., 2023). Our finding for the TSS value of the cactus pear and strawberry fruits blended jam product was measured as 57.875 ± 3.51 °Brix. The lower TSS value in our observation could be due to the pectin-sugar-acid interaction favoring gel development rather than remaining available as free soluble solids (sugars) (Bekele et al., 2020). However, studies have also shown fruit jams with lower 63 °Brix can

be developed. Jribi et al. (2021) developed a low-sugar (48.87 °Brix) strawberry jam by blending the fruit with stevia as a sweetener. They reported that incorporating stevia led to significant improvements in the physicochemical composition, color indexes, and textural parameters of the final product.

Chalchisa et al. (2022) studied the effect of processing temperature (at 90 and 105°C) on the total soluble solids (TSS) of smooth cayenne pineapple jam production. In their report, cooking temperature showed an insignificant influence on the final fruit jam. In our observation, the interactive effects of the blending ratio with cooking temperature and time lead to different TSS values in the produced cactus pear and strawberry fruits blended jam, which could influence its physicochemical composition and sensory properties. The production of fruit jam involves complex physical and chemical changes. Processing parameters including fruit composition (initial TSS, acidity/pH, and pectin content), blending ratios, and evaporation are interdependent. Strawberry fruit typically has a lower initial TSS than many other fruits (Table 8), the specific blending ratio of these two fruits determines the mixture's initial composition. This, in turn, influences the cooking time and temperature required to reach the target TSS for a stable jam.

3.2.3. Effect of process variables on vitamin C (Vit C)

The vitamin C concentration of the produced cactus pear and strawberry fruit-blended jam is affected by the linear term of cooking temperature, but the strawberry fruit blending ratio showed a less significant effect. Interactive terms of cooking time with temperature and blending ratio, as well as all quadratic terms, also play a role. However, the linear term of cooking time and interactive effects of time with temperature have shown insignificant ($p > 0.1$) effects (Table 5). The quadratic terms of the input variables, which showed significant effects ($p < 0.1$) on the vitamin C content of the jam, were employed to develop a quadratic model (Equation 4) to predict the concentration.

Blending fruits and cooking for a longer time could decline the vitamin C concentration of a fruit jam production. Elevated temperatures exacerbate the loss of vitamin C (Güder et al., 2014; Martinsen et al., 2020). This is due to the fact that vitamin C (ascorbic acid) is sensitive to heat, light, and high temperature. In particular, an increase in fruit jam processing temperature accelerates the hydrolysis of dehydroascorbic acid (DHAA) to 2,3-diketogulonic acid, followed by chemical reactions of oxidation, dehydration, and polymerization (Martinsen et al., 2020). The insignificant effect ($p > 0.1$) in the linear term of cooking time on the vitamin C concentration in the present study perfectly relate to this fact. This negative effect indicates that at longer cooking times, the vitamin C content could decline. Besides, the linear and quadratic terms of the cooking temperature, as well as the interactive effect with cooking time in our findings (Table 5), supports this fact.

In the present study, strawberry fruit blending ratio was considered as an input factor shown less significant effect on the vitamin C content of the final jam. This could be due to the major degradation of vitamin C that occurs during thermal processing (cooking), rather than the blending ratio of the strawberry fruit concentration.

Chalchisa et al. (2022) studied the effect of processing temperature (at 90 and 105) on vitamin C of pineapple jam (smooth cayenne) production. An average of 7.74 to 9.9 mg/100 g vitamin C concentration was decreased in their report. During the processing of fruit jam from strawberry (cv. *Senga Sengana*) and raspberry (cv. *Veten*) the processing temperature at 60, 85 or 93 °C lead to significant losses of ascorbic acid, total monomeric anthocyanins (TMA) and total phenolics (TP) (Martinsen et al., 2020).

Over all, particular factors that lead to vitamin C degradation are oxidation, temperature dependence, light sensitivity, oxygen exposure, and the presence of metal ions (Scrob et al., 2022). Further studies that consider optimization of the presence of metal ions and any exposure to oxygen during cactus pear fruit jam processing and storage are very important.

Table 5: Quadratic analysis of Variance (ANOVA) for Vit C

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	7.11	9	0.7896	3.83	0.0240 **
A-Temp.	2.61	1	2.61	12.66	0.0052 **
B-Time	0.0656	1	0.0656	0.3177	0.5854
C- Blending ratio	0.6185	1	0.6185	3.00	0.1141*
AB	0.8450	1	0.8450	4.10	0.0705 **
AC	0.1250	1	0.1250	0.6058	0.4544
BC	0.6050	1	0.6050	2.93	0.1176*
A ²	1.38	1	1.38	6.68	0.0272**
B ²	0.7522	1	0.7522	3.65	0.0853**
C ²	0.5933	1	0.5933	2.88	0.1208*
Residual	2.06	10	0.2063		
Lack of Fit	1.63	5	0.3257	3.74	0.2869
Pure Error	0.4350	5	0.0870		

**Model terms are significant at $p < 0.1$, *Model terms are less significant at $p < 0.2$, and other values of model terms are insignificant.

Table 6: Summary of model adequacy measures for all responses

Statistical parameter	Statistical value		
	TA	TSS	Vit C
Std. Dev.	0.1812	3.51	0.446
Mean	2.31	48.61	5.74
C.V. %	7.83	7.22	7.91
R ²	0.395	0.8213	0.7613
Adjusted R ²	0.3238	0.7575	0.5878
Predicted R ²	0.1356	0.5613	0.1302
Adeq Precision	6.8968	10.3646	5.9798

3.3. Model equations development

Using RSM, model equations were developed to establish empirical relationships between the response functions (TA, TSS, and Vit C) and the independent variables (blending ratio, time, and temperature). Their mathematical relationships were determined Design-Expert software. Final equations, excluding non-significant terms, were created and presented in Equations 2, 3, and 4. Notably, some insignificant terms with significant interaction or quadratic effects were included in the model.

Model adequacy was checked using regression coefficients (R^2), adjusted regression coefficient ($\text{adj-}R^2$), Predicted R^2 ($\text{pre-}R^2$), Adeq. Precision, and Coefficient of variation (C.V). Model adequacy for all responses is summarized in Table 6.

Adequacy Precision measures the signal-to-noise ratio; a ratio greater than 4 is desirable (Feng et al., 2017). All the predicting models' ratios are greater than 4, indicating an adequate signal. Hence, these models can be used to navigate the design space.

Besides, the Coefficient of Variation (C.V, %) is a statistical measure used to assess the variability of the data points around the mean. All observed predicting models have a C.V below 10%, which is often considered desirable (Feng et al., 2017). Except for the titratable acidity ($R^2 = 0.395$), the coefficient of determination (predicted R^2) for the TSS and Vitamin C predictive models are greater than 0.7, which is desirable to validate the models (Tsegay et al., 2024).

$$\text{TA} = 1.26 + 0.0078 * \text{Temp} + 0.03 * \text{Ratio}$$

(2)

$$\text{TSS} = - 3.93 - 0.445 * \text{Temp} + 5.03 * \text{Time} - 1.14 * \text{Ratio} + 0.069 * \text{Temp} \\ * \text{Ratio} - 0.25 * \text{Time} * \text{Ratio}$$

(3)

$$\text{Vit C} = - 17.82 + 0.3 * \text{Temp} + 0.53 * \text{Time} + 0.67 * \text{Ratio} + 0.013 * \text{Temp} \\ * \text{Time} - 0.022 * \text{Time} * \text{Ratio} - 0.003 \\ \text{Temp}^2 - 0.035 * \text{Time}^2 - 0.008 * \text{Ratio}^2 \quad (4)$$

Where TA represents for total titratable acidity; TSS for total soluble solids; Vit C for vitamin C; and Temp for temperature.

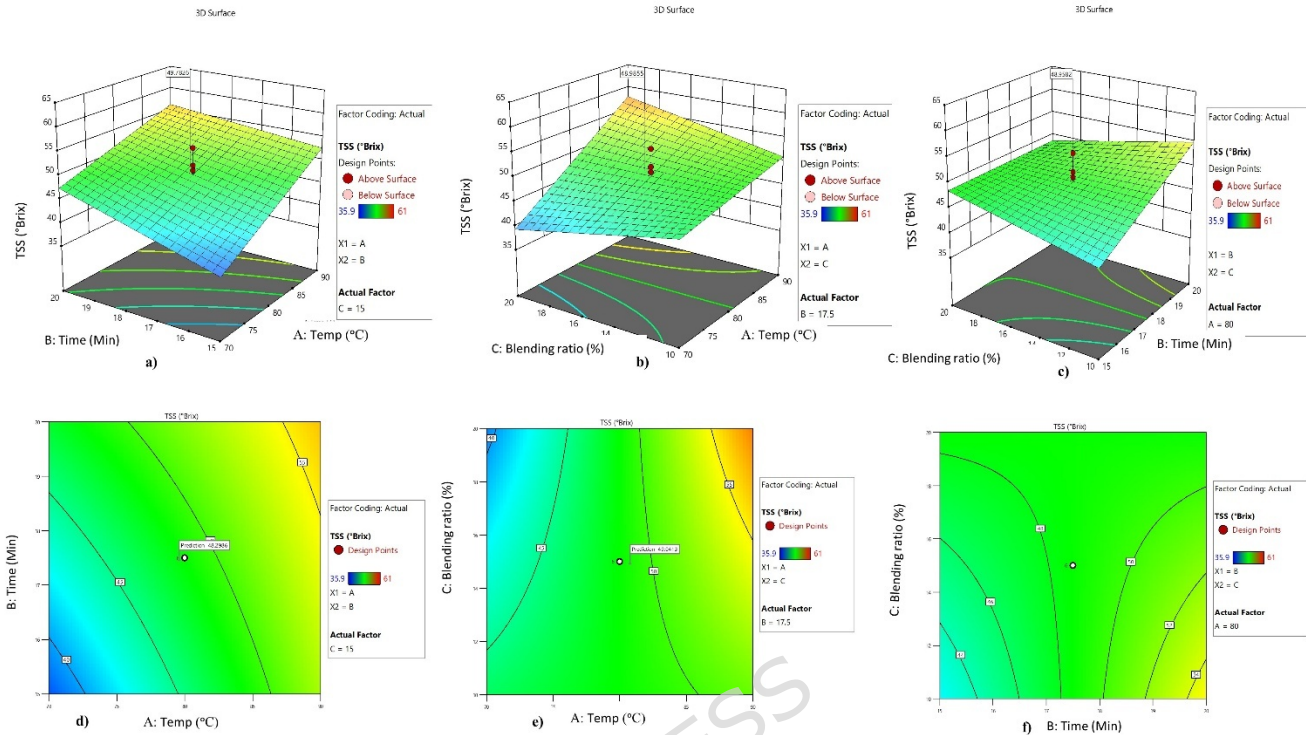


Fig. 2: 3D response surface and 2D contour plots illustrating the relationships and effects of blending ratio, cooking time, and temperature on the total soluble solids of the produced jam: a) Interactive effects of cooking time (min) and temperature (°C) at a constant blending ratio (15%); b) Interactive effects of cooking temperature (°C) and blending ratio (%) at a constant cooking time (17.5 min); and c) Interactive effects of cooking time (min) and blending ratio (%) at a constant cooking temperature (°C).

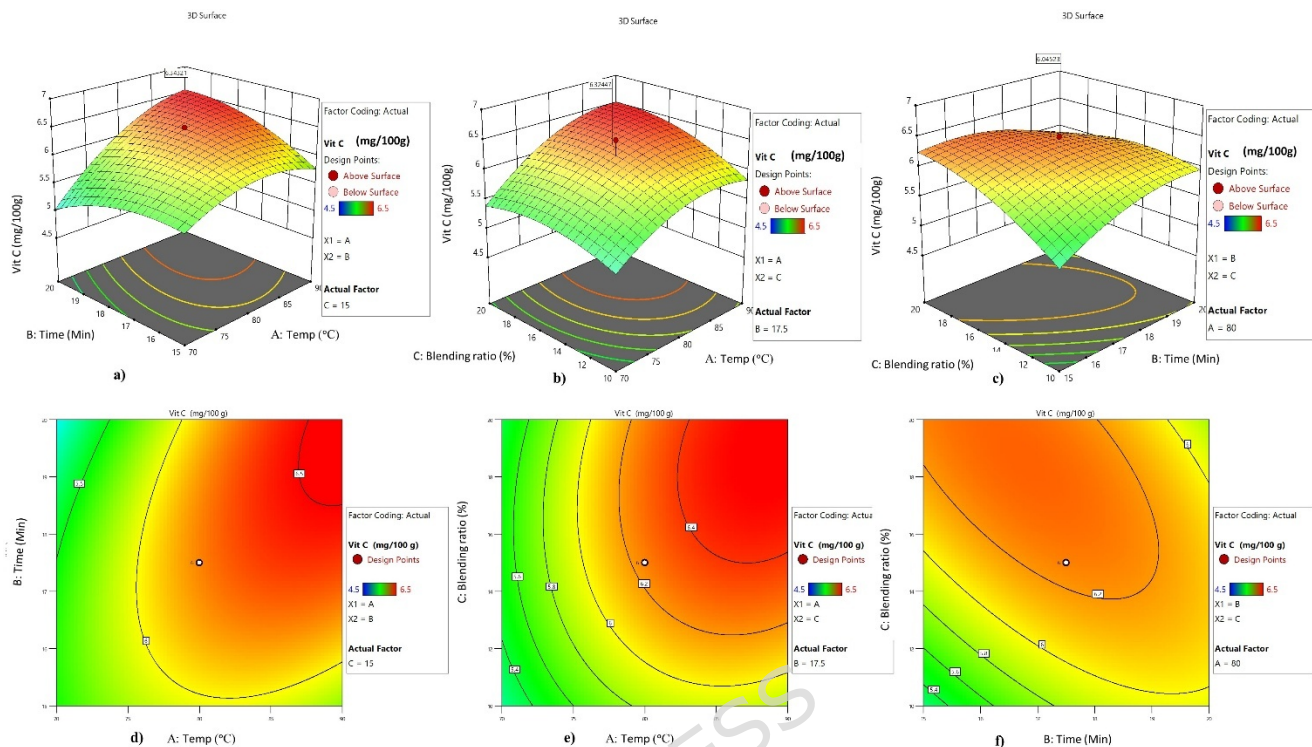


Fig. 3: 3D response surface and 2D contour plots illustrating the relationships and effects of blending ratio, cooking time, and temperature on the vitamin C content of the produced jam: a) Interactive effects of cooking time and temperature ($^{\circ}\text{C}$) at a constant blending ratio (15%); b) Interactive effects of cooking temperature ($^{\circ}\text{C}$) and blending ratio (%) at a constant cooking time (17.5 min); and c) Interactive effects of cooking time (min) and blending ratio (%) at a constant cooking temperature (80°C).

3.4. Optimization of significant factors

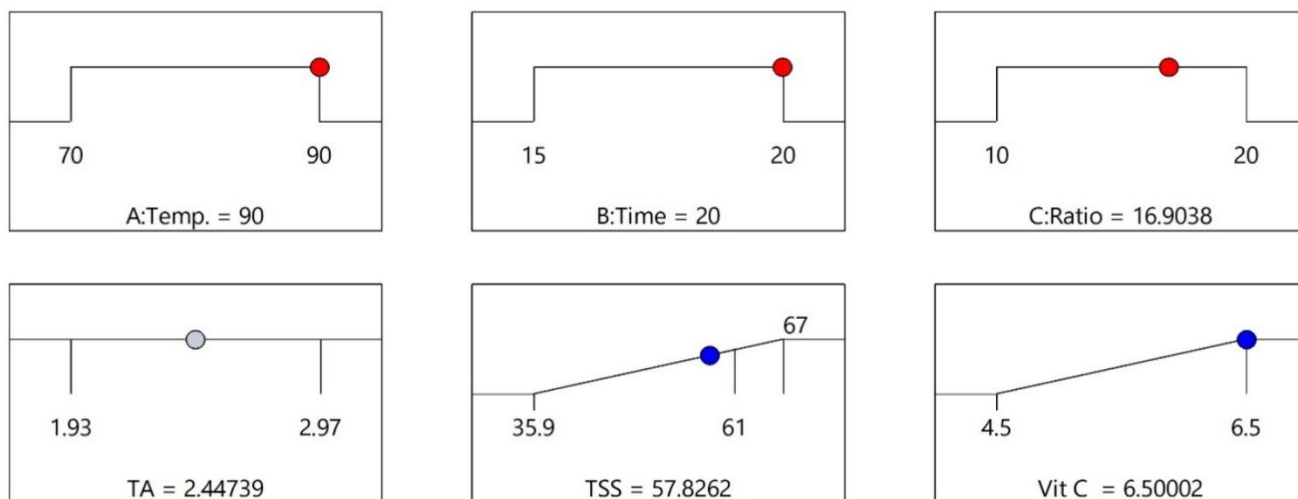
To determine the optimum predictive values of the jam cooking variables, the statistical analysis software package Design-Expert version 10.0.3 was employed. Table 2 shows the expected and confirmation report for optimization of the jam processing variables.

The 3D surface plots and 2D contour plots depicted in Figures 2 and 3 provide a visual representation of the relationship between jam processing factors and the responses (total soluble solids and vitamin C content), which helps to identify optimal conditions. The RSM outcomes depicted in Figure 3 clearly show curvature and fluctuations (non-linearity) in these graphs, driven by the processing effects of cooking temperature, time, and the strawberry fruit blending ratio on the final jam Vitamin C content. At the peak of the RSM

graphs (Figures 3A-3C), this curvature is crucial for achieving the optimum Vit C content (from 6.045 to 6.343 mg/100g). The jam processing factors (cooking temperature and time) resulted in more significant curvature (indicating significant quadratic terms) for reaching the optimum point than the effect of the strawberry blending ratio. However, the processing factors for optimizing TSS and TA did not exhibit significant curvature or fluctuations; instead, the factors demonstrated linearity for the TA response and a two-factor interaction effect for the TSS.

Fruit jam qualities such as titratable acidity, total soluble solids, and vitamin C content are important for better stability, nutritional and sensorial acceptability during storage as well as distribution. Therefore, all responses were given equal weightage to get as much as a maximum response. Based on this assignment of weights to the responses, jam processing parameters are optimized for multi-responses as shown in Figure 4.

Using the desirability function approach to get the combined optimum cooking parameters, a two-side transformation was applied, and the desirability function approaches to unity was selected (Tsegay, 2020). Figure 4 shows the optimum desirable function, cooking temperature, time, and blending ratio. Hence, at a desirability function of 0.84 and at the optimum cooking temperature (90 °C), time (20 min), and blending ratio (16.9%), compositions of the jam with 2.45% total acidity (TA), 57.8 °Brix of total soluble solids (TSS), and 6.5 mg/100g citric acid of vitamin C can be achieved.



Desirability = 0.840

Fig. 4. Numerical optimization of jam cooking parameters using a desirability ramp. The variables are represented as: Temp = Temperature ($^{\circ}\text{C}$), TA = Titratable Acidity (% citric acid), TSS = Total Soluble Solids ($^{\circ}\text{Brix}$), and Vit C = Vitamin C (mg/100g).

3.5. Validation and confirmation of the developed predictive models

The validity of the predictive models for TA, TSS, and vitamin C was assessed using standard deviation, R^2 , Adjusted R^2 , and Predicted R^2 values, all detailed in Table 5. The Adeq Precision scores of 6.89, 10.36, and 5.98 indicate that the models have adequate signal for predicting the variables, as a ratio greater than 4 is desirable (Montgomery, 2017). While the Predicted R^2 values for TA and TSS agree with the Adjusted R^2 , the Predicted R^2 for vitamin C slightly differs by more than 0.2.

Four confirmatory experiments were conducted at the developed predicted optimum values. It is confirmed that the model's predictions for the optimal jam processing conditions (90°C , 20 min, and the strawberry fruit blending ratio of 16.9%) which resulted in values of $2.075 \pm 0.18\%$ (acid) TA, 57.823 ± 3.5 $^{\circ}\text{Brix}$ TSS, and vitamin C of 5.95 ± 0.45 (mg/100g ascorbic acid). These

experimental results align with the predicted values shown in Table 7 and are statistically consistent (t-test, $t_{0.05,3}$).

Table 7: Constraint and confirmation report for optimization of the jam processing variables

Constraint s	Set values			Measure d data mean	Predicted d mean	SE Pred.	Std. dev.
	Goals	Lower limit	Upper limit				
Temp. (°C)	90.00	70.00	90.00				
Time (min)	20.00	15.00	20.00				
Blending ratio (%)	16.90	10.00	20.00				
TA (% Acid)	2.4739	1.9922 6	2.4810 5	2.075	2.4739	0.10399	0.18121 3
TSS (°Brix)	57.826 2	44.670 6	60.516 6	57.875	57.8262	2.06219	3.51048
Vit C (mg/100g)	6.5000 2	5.2939 2	6.5545 1	5.975	6.50002	0.28637 1	0.44602 5

3.6. Chemical and microbial qualities of the produced jam

Physicochemical properties of the fruits and jam processing factors play an important role in jam product development. Hence, considering the initial qualities of blending fruits, optimizing jam processing based on prominent physicochemical parameters was found crucial. Data for chemical qualities of individual blending fruits and the developed jam are presented in Table 8. Moreover, measured data for microbial quality and shelf life of the developed jam are presented in Table 9.

Fruit jams can be prepared from mixtures of sugars, pulp and/or puree of one or more kinds of fruit, acidulants, pectin, and/or other flavoring agents (Okut et al., 2018). Jam development is a means for convenient preservation of fruits. However, many jam quality parameters can be deteriorated during inappropriate processing methods, packaging, storage, and due to the quality of raw materials used. These factors determine the jam's final quality, sensorial acceptance, as well as market value. Mainly, during jam production, employing high-temperature cooking can significantly affect its overall

quality and shelf life (Korus et al., 2015). Choosing adequate ingredients and processing conditions is crucial to produce a high-quality jam product, which substantially increases the physical-chemical propensities, like total soluble solids and titratable acidity (Chalchisa et al., 2022).

In the present study, we developed jam from a blend of cactus pear and strawberry fruits at the optimized values of processing factors (Table 7) and characterized. In particular, the jam was made at a cooking temperature of 90°C for 20 minutes, with a strawberry fruit blending ratio of 16.9%. The quality indicators analyzed included titratable acidity (TA), pH, total soluble solids, vitamin C concentration, total plate count, and yeast and molds. The summarized results for these values are presented in Table 8.

To illustrate the quality changes that occurred during processing, the titratable acidity, pH, total soluble solids, and vitamin C concentration of the individual fruits used in the blend were also analyzed and are shown in Table 8. The pH and TA values found in this study are consistent with those reported for jam produced from pineapple fruits (Chalchisa et al., 2022). However, the total soluble solids (TSS) and vitamin C contents are higher in our results. A similar result was reported for pH (3.38) in jam produced from cherry (Rababah et al., 2014), though that study noted lower soluble solids (66.3%). Furthermore, jam produced by blending natural (Stevia) sweeteners and strawberry fruit was characterized as having a pH of 3.25, 0.569 g citric acid/100 g total acidity, 48.87 °Brix soluble solids, 110 CFU/g total mesophilic flora, and <10 CFU/g of yeasts and molds (Jribi et al., 2021). The main reason for the difference in our observation and other studies is attributed to the variability of initial ingredients utilized and processing methods. The detailed individual analysis of quality indicators is presented below.

Table 8: Chemical and microbiological qualities of cactus pear and strawberry fruit juices and the produced jam

Quality parameter	Cactus pear	Strawberry	Jam product (16.9% strawberry)

pH	6.03 \pm 0.05	4.5 \pm 0.25	3.2 \pm 0.3
TA (% Citric acid)	0.17 \pm 0.03	1.5 \pm 0.1	1.9 \pm 0.12
TSS ($^{\circ}$ Brix)	13.6 \pm 0.35	6.7 \pm 0.2	58.6 \pm 0.72
Vit C (mg/100g)	26.7 \pm 0.15	35.3 \pm 1.5	6.8 \pm 0.51
Total plate count (CFU)/g	ND	ND	2.6 \pm 0.15
Yeast and mold (CFU)/g	ND	ND	< 1

TA = total acidity, TSS = total soluble solids, Vit = vitamin, ND = not determined

3.6.1. Titratable acidity (TA) and pH of the produced jam

The acidity of a jam product is a dominant quality parameter that influences its stability and shelf life (Chalchisa et al., 2022). Afoakwa et al. (2023) reported that the pH of jams produced from pineapple pulp and by blending with 70% orange-fleshed sweet potato pulp were 3.2 and 3.02, respectively. Moreover, acidity and pH are critical factors for jam stability and achieving optimum gel conditions, with the ideal pH range for proper jelling being from 3.2 to 3.6 (Jribi et al., 2021).

Our pH result in the produced jam (3.2 \pm 0.3) is consistent with this range. It is also consistent with the results for apple jam produced by adding different amounts of date and orange (ranged from 1.2% to 1.9% acidity) (Haroon et al., 2024). The added pectin from orange peel and lemon juice as an acidulant could have enhanced the pH value of the jam. However, our result for total acidity (1.9 \pm 0.12% citric acid) is beyond the optimal range. The optimal range for the total acidity of jams is between 0.50% and 0.80% citric acid. If the acidity goes beyond 1%, syneresis (the separation of liquid from a gel) can occur. Excessive acidity weakens the pectin gel network, causing it to discharge trapped liquid (Sunarharum et al., 2021).

3.6.2. Total soluble solids (TSS) of the produced jam

Total soluble solids (TSS) in fruits is considered as an index of sweetness, which is dependent on the fruit's maturity and growing conditions. It is also dependent on added sugar during jam processing, which affects the physical

and chemical features of pectin gelation. Besides, the presence of high sugar in jam products absorbs moisture, protects against microbial development, and enhances shelf life (Haroon et al., 2024).

In the present study, the total soluble solids measured in the produced jam is 58.6 ± 0.72 °Brix. This is higher than the jam produced by blending natural (Stevia) sweeteners and strawberry fruit (48.87 °Brix) (Jribi et al., 2021). It is also slightly higher than apple jam produced by adding different amounts of date and orange (ranging from 43 to 51 °Brix) (Haroon et al., 2024). This suggests that the cactus pear and blended strawberry fruits, combined with optimized processing factors, were effective in developing a jam with improved total soluble solids (TSS). Furthermore, the initial levels of soluble solids including sugars, organic acids, minerals, and pectin in the blended fruits and added ingredients were suitable for jam production. However, it is lower than the total soluble solids reported in other jams. For instance, the total soluble solids in jams produced from pineapple pulp and by blending with 70% orange-fleshed sweet potato pulp contained 65.4 and 64.56 °Brix, respectively (Afoakwah et al., 2023). A previous study also reported higher TSS in apple jam (66.66 °Brix) (Haroon et al., 2024). The differences in our findings and other reports could be due to variations in raw materials, the blending of other ingredients, and/or processing methods.

Most fruit jams are required to achieve a final TSS (total soluble solids) concentration of at least 65% to 68% to ensure proper gelling, texture, and shelf stability. Variations in TSS between different types of jams are primarily a result of specific formulation requirements based on the natural composition of the fruit and specific regulatory standards. Different fruits naturally contain varying levels of soluble solids (sugars, organic acids, minerals, and pectin) which determine the final jam TSS quality.

3.6.3. Vitamin C concentration of the produced jam

The measured vitamin C in the developed jam (Table 8) is slightly lower than that reported by Chalchisa et al. (2022) for a jam produced from pineapple fruits (ranging from 7.74 to 9.9 mg/100 g). The reduced amount of vitamin C

in the developed jam and the raw material fruits could be due to differences in the raw materials' origin and the effects of processing temperature (90 °C) and time (20 min).

Vitamin C (ascorbic acid) content is an important attribute in fruit jams and can be deteriorated by both temperature and light. Cooking fruit jams at elevated temperatures significantly negatively impacts total ascorbic acid. Besides, balancing the total soluble solids (TSS) and blending time could affect the total ascorbic acid content, as reported by Chalchisa et al. (2022). They also reported that if the TSS is increased to 60 °Bx, the total vitamin C can be enhanced to about 10.8 mg/100 g; however, when the TSS reaches 67 °Bx, the total ascorbic acid decreases to 7.45 mg/100g. Therefore, aiming to achieve better TSS consideration to protect the loss of ascorbic acid is crucial.

Jams produced from pineapple pulp and by blending with 70% orange-fleshed sweet potato pulp contained 30.2% and 19.2% vitamin C, respectively (Afoakwah et al., 2023). This study clearly implicates that selecting appropriate ingredients to blend with fruits rich in sugar content, like cactus pear fruit could also help achieve better vitamin C content in the final jam.

3.6.4. Microbial loads (Total plat count and yeast and mold counts) of the produced jam

The maximum authorized levels of microorganisms during non-standard analyses of total bacteria count for jams and purees from fruit or berries product is 5×10^3 (CFU)/g and for the yeasts and molds is 50 (FAO, 2000). In another study, the acceptable standard levels for molds and yeasts and total mesophilic flora (total number of bacteria and other microorganisms) are 10^3 and 10^5 (CFU)/g respectively. Moreover, low-sugar jams contained pH values lower than 4, are considered microbiologically stable (Jribi et al., 2021). In our study, the measured values for total plat count (total number of bacteria and other microorganisms) and yeast and molds are in an acceptable limit which are shown in Table 8. The results are also consistent with other studies. For instance, the total plate count in jams produced from pineapple pulp and

by blending with 70% orange-fleshed sweet potato pulp contained 8 (CFU)/g and 4.5 (CFU)/g respectively, and the yeast and mold were reported empty. Moreover, these results are lower than the values reported on mixed fruit jam made from natural and artificial sweetener (yeast and mold from 7.19 to 10.03 (CFU)/g) and low-calorie jam with natural sweetener stevia (yeast and mold about 11.05 (CFU)/g) (Haroon et al., 2024; Sutwal et al., 2019).

In jam products, microbial differences stem from high sugar content and low pH, conditions that inhibit most bacteria but allow spoilage primarily by acid-tolerant yeasts and molds. Jams are high-acid foods (typically pH below 4.0) with low water activity, an environment hostile to bacterial growth. Moreover, yeasts and molds are more acid-tolerant than bacteria, thriving in jams' low moisture and high sugar conditions (Jribi et al., 2021). Consequently, in the present study, the measured total soluble solids (TSS), pH, and titratable acidity of the cactus pear fruit blended jam could lead to better stability during storage.

3.7. Overall quality during shelf life of the produced jam

The cactus pear and strawberry fruits blended jams produced at the optimized cooking parameters (cooking temperature of 90°C, time of 20 min, and the strawberry fruit blending ratio of 16.9%) were preserved using air fastened glass jars at light protected area and room temperature (25 °C). Then, shelf life qualities (as shown in Table 9) were analyzed first for one, two and three months then for 6 and 9 months. Figure 5 depicts shelf life prediction of the produced jam employing the kinetic reaction models.

A 9-month timeframe provides sufficient data points (e.g., tests at 0, 3, 6, and 9 months) for predictive modeling, allowing the application of Arrhenius equations to determine kinetic rates of quality loss (Phan et al., 2014). To balance the need for better quality prediction with resource allocation, we included specific exclusions: shorter studies might not reveal long-term degradation trends, and studies longer than a year increase storage cost.

The shelf life of the produced fruit jam was assessed by evaluating TA, TSS, Vitamin C degradation, and microbial quality (total plate count, yeast, and

mold). Because TA, TSS, and Vitamin C are primary indicators of chemical, nutritional, and organoleptic (flavor/aroma) deterioration, their changes were monitored throughout the storage period. Furthermore, TA, which measures the total acid content, was considered a representative index of the organic acids present in the jam (Rashid et al., 2021). Hence, during storage, these organic acids can decrease (if respiration continues, as in fresh produce) or increase (due to microbial growth), affecting the sourness and overall flavor balance. TSS indicate the sugar content of fruit jam products, which correlates with sweetness. Changes in TSS, often an increase due to water loss or a decrease due to sucrose breakdown could help to monitor the decomposition of sugar content during storage. Since vitamin C is highly sensitive to oxidation and light during storage, it is an excellent index for evaluating overall nutritional degradation. Its rapid decline, especially in jams, acts as a marker for the loss of overall nutritional value (Rashid et al., 2021).

Many factors such as storage temperature, pH, ascorbic acid, presence of hydrogen peroxide, structure and concentration of anthocyanins, and difference in cultivars determine color quality of fruit jams (Patras et al., 2011). Browning is a discoloration of fruit products like jam that can be developed during enzymatic browning by the activity of enzymes such as peroxidase (POD), polyphenol oxidase (PPO), and phenylalanine ammonia-lyase (PAL) when the food products are exposed into oxygen. This discoloration effect deteriorates quality attributes like appearance and nutritional values of jams. These browning or discoloration are outputs of defects (exposing to oxygen or over processing) during fruit jam processing techniques such as blanching, chemical treatments, proportion of pectin, packaging, freezing, and/or herbal treatments (R et al., 2024).

In the present study, although the jam samples were stored using air fastened glass jars at light protected area, we observed that slight browning or discoloration in the produced jam occurred after 6 months of storage time at 25 °C. This effect can be attributed to the added pectin extract, improper

packaging (exposing the jam to oxygen), or an insufficient cooking temperature (90 °C) to deactivate enzymatic activity. Jams packaged in glass jars with more free space (creating headspace) exhibited significantly more browning or discoloration than those in jars with smaller headspace.

Martinsen et al. (2020) reported that raspberry jams cooked at 85 °C and stored at room temperature (23 °C) for 16 weeks showed significantly lower Chroma (a duller, darker color). Moreover, storing jams at higher temperatures (35 °C) causes them to develop a darker color and reduced yellowness and redness, which is due to the conversion of anthocyanins and phenolics into brown, water-insoluble pigments with increasing storage time (Dubey et al., 2021).

Browning or discoloration effect can be reduced by inactivating the responsible enzymes employing optimum heating, reducing the pH on the fruit surface (applying lemon juice or other food grade acids), protecting exposing to oxygen or adding other health recommended food grade preservative like sulfur dioxide (Aimi Azira et al., 2021). Hence, future studies should focus on the browning effect during storage of jam produced from cactus and strawberry fruits might be important.

3.7.1. Shelf life of the produced jam based on titratable acidity (TA) and total soluble solids (TSS)

Many storage conditions such as temperature, time, humidity, exposure to light, etc. and the jam compositions like pH, moisture content, acid, sugar, active enzymes, microbial loads, etc greatly determine fruit jam's shelf life (Haroon et al., 2024; Prisacaru et al., 2025). For instance, the effect of titratable acidity (TA) on the shelf life of fruit jams is due to the higher titratable acidity inhibits microbial growth. Hence, the optimal range of titratable acidity in jams could enhance its shelf life (Brandão et al., 2018). The slight increase in titratable acid in our findings is consistent with this study. The increase in acidity during storage are attributed for the breakdown of polysaccharides, pectin substances, oxidation of reducing sugars, or due to the added lemon juice (Prisacaru et al., 2025). The subsequent slight

increase in total soluble solids in our findings is consistent with studies reported by Menevseoglu et al. (2020) and Brandão et al. (2018). This is due to the temperature effect, as solubility can be facilitated at approximately 25 °C.

Change in pH, titratable acid and soluble solids could affect the nutritional and sensory qualities like firmness of the fruit jam. Although strawberry jam firmness does not significantly change with increase in storage time at room temperature (at 25 °C), it can be decreased during storage as a result of high temperature (after 15 days at 55 °C). The scientific reason of this firmness decrease is due to the pectin underling either acid- or base-catalyzed depolymerization at an elevated temperature (Rababah et al., 2014).

3.7.2. Shelf life of the produced jam based on microbial load

Microbiological stability in a fruit jam sample is a key indicator of storage conditions and its chemical composition. Beyond environmental factors, the moisture content, sugar level, pH, and types of acids present are responsible for the development of microbes. The metabolic activities of these microorganisms affect the shelf life, sensory acceptance, and overall quality of the jam (Haroon et al., 2024). Due to this, legislation sets permissible limits of microbial loads for safe consumption. For instance, the permissible limit for the total yeast and mold (YM) count in jams should be below 10^4 (CFU)/g (Dubey et al., 2021).







The total plate count and total yeast and mold measured in our findings shown increase during the storage time period and at 25 °C storage temperature (Table 9). However, the total yeast and mold measured values are below the permissible limits for safe consumption (Haroon et al., 2024). It is also below the values that other studies reported such as 1 to 8 (CFU)/g in low calorie apple jam with natural sweetener stevia (Sutwal et al., 2019), and 1.35×10^2 (CFU)/g in reduced calorie aloe vera (*Aloe barbadensis* Miller) based pineapple fruit jam. Moreover,, the yeast and mold measured in apple fruit jam stored at 25 °C for 60 days was reported as 7.19–10.03 (CFU)/g (Haroon et al., 2024). The main reason for the low growth in yeast and mold

in the present study could be the pH of the cactus pear and strawberry fruit blended jam is low (pH of 3.2). Besides, the acidity level of the jam measured in our findings could create better stability.

Presence of intermediate humidity levels up to 40% in jams could cause development of total plate count which lead to quality deterioration and less shelf life. In the present study, the total plate count increased from 2.6 to 10.36 (CFU)/g in 9 months storage time and at 25 storage temperature. These results are lower than the values reported on mixed fruit jam made from natural and artificial sweetener (from 7.19 to 10.03 (CFU)/g) (Haroon et al., 2024); low-calorie jam with natural sweetener stevia (11.05 (CFU)/g) both stored for 60 days (Sutwal et al., 2019); and in orange-fleshed sweet potato-pineapple blended jam (from 4.5 to 8 CFU)/ g (Afoakwah et al., 2023). The main reason for the difference in our measured value compared with these reported studies could be due to TSS, pH, and acidity content, which in turn determine the growth of total plate count.

Increase in storage temperature increases the moisture content which facilitates microbial growth (Haroon et al., 2024). In a reduced calorie aloe vera (*Aloe barbadensis* Miller) based pineapple fruit jam containing pH range of 3.18 to 3.34 and storage temperature of 25 °C, the total yeast and mold (YM) count was reduced and it was found that free from any coliforms (Dubey et al., 2021).

Table 9: Shelf-life qualities of jam stored in glass jars at room temperature (at 25 °C).

Quality Indices	Storage time (in month)					
	 0	 1	 2	 3	 6	 9
TA (% Citric acid)	1.9 ±0.12	1.87 ±0.02	1.97 ±0.015	2.06 ±0.06	2.27 ±0.02	2.42 ±0.021

TSS (°Brix)	58.6 ±0.72	59.4 ±0.46	60.23 ±0.06	60.5 ±0.02	61.4 ±0.1	61.9 ±0.1
Vit C (mg/100g)	6.8 ±0.51	6.4 ±0.06	6.2 ±0.11	5.8 ±0.07	4.5 ±0.03	3.7 ±0.02
Total plate count (CFU)/g	2.6 ±0.15	2.85 ±0.05	3.5 ±0.1	5.13 ±0.6	7.2 ±0.08	10.36 ±0.15
Yeast and mold (CFU)/g	< 1	1.3 ±0.1	2.1 ±0.2	2.8 ±0.03	5.66 ±0.055	7.5 ±0.17

TA = total acidity, TSS = total soluble solids, Vit = vitamin

3.7.3. Predicting jam shelf life through Vitamin C degradation

A decrease in vitamin C content in fruit jams during storage is expected especially at increased storage temperature and time.

In determining the shelf life of fruit jam based on vitamin C (ascorbic acid) degradation, the acceptable level of degradation varies due to fruit sources, light and oxygen exposure, the addition of different sweetening agents, and storage temperature and time (Scrob et al., 2022). Generally, vitamin C loss during storage could be within 20% to 35% over a 3-6-month period at room temperature (approx. 20-25°C). Although vitamin C degrades quickly due to its thermal sensitivity and oxidation, a 30% loss is often tolerated before it is considered a significant loss of nutritional quality (Poiana et al., 2011).

In our findings, vitamin C concentration of the produced blended fruit jam was reduced from 6.8 to 3.7 mg/100g at 9 months storage period and at room temperature (25°C) as shown in Table 9. This scenario is consistent with other reported studies. For instance, Brandão et al. (2018) reported that at 105 days of storage vitamin C content in a dietetic functional mixed cerrado fruit jam was reduced from 50 mg/100g to 20 mg/100g at 25°C. Similarly, at increased storage time from 7 to 28 days and temperature from 4 to 15 °C the ascorbic acid (Vitamin C) in a jam was reduced from 70% to 29.6% (Patras et al., 2011). Oxidation, temperature dependence, light sensitivity, oxygen exposure, and the presence of metal ions could be the main factors that lead to vitamin C degradation during storage and distribution (Scrob et al., 2022).

Therefore, to ensure and enhance the benefit of vitamin C in fruit jams, fruit sources and ingredients have to be properly processed, and appropriate storage conditions should be stated.

Kinetic models, such as the Arrhenius equation, are used for the rapid and cost-effective evaluation of changes in critical quality parameters with time variation (Kim et al., 2022). These parameters include color, browning, and ascorbic acid degradation during both storage and processing. Specifically, the degradation of compounds like anthocyanins and ascorbic acid often follows zero or first-order kinetics and can be predicted using the Arrhenius equation (Patras et al., 2011). Similarly, the Arrhenius reaction kinetic models are suitable for analyzing the degradation of physicochemical properties and vitamin C content employing these zero and first-order reactions (Kim et al., 2022).

For a zero-order reaction, the concentration of a substance, such as vitamin C, decreases consistently over time (Kim et al., 2022). Equation 5 expresses the extent of this degradation rate, quantifying the change from an initial concentration (C_0) to a specific concentration (C) over a storage time (t), which we tested its suitability for the developed jam (Kim et al., 2022).

$$C = C_0 - kt \quad (5)$$

Using the zero-order reaction model, Equation 6 was applied to determine the extent of vitamin C degradation in the jam at the end of the shelf life (t_s).

$$t_s = \frac{C_0 - C_e}{k} \quad (6)$$

Where C_0 is an initial concentration (Vitamin C), C_e is the extent of change in vitamin C, t_s shelf life (in months), k is the zero-order reaction rate constant (months^{-1}), and t is the time (month).

For a first-order reaction where vitamin C concentration decreases over time, Equation 7 was employed to describe the Vit C degradation kinetics. Alternatively, to calculate the vitamin C concentration at the end of

the product's shelf life (t_s), where the final concentration is defined as C_e , a specific equation (Equation 8) that incorporates C_e was applied.

$$\ln \frac{C_0}{C_e} = kt_s$$

$$\ln C = \ln C_0 - kt \quad \text{or} \quad \ln C_0/C = kt \quad (7)$$

Then, the shelf life prediction due to the vitamin C degradation following the first order reaction was calculated using Equation 8.

$$t_s = \frac{\ln \frac{C_0}{C_e}}{k} \quad (8)$$

Where C_0 is an initial concentration (Vitamin C), C is a concentration content (Vitamin C) at certain time, C_e is the extent of change in vitamin C, t_s shelf life (in months), k is the first order reaction rate constant (months^{-1}), and t is the time (month).

In both the zero order and first order kinetic models, the Equations 5 and 7 are straight lines and the rate order or rate of vitamin C reduction (*slope or -k* in months^{-1}) was determined from the developed straight-line equation as shown in Figure 5.

The negative Pearson's r value in both zero order and first order kinetic models shown in Figure 5 indicates a negative linear correlation between the time and vitamin C degradation variables (when one variable increases, the other tends to decrease, and vice versa), in which the closer the value to -1 indicates the stronger the negative correlation (Kim et al., 2022).

Both the developed zero order ($R^2 = 0.99195$) and first order ($R^2 = 0.99168$) kinetic models shown similar shelf life prediction capacity of the produced jam. However, the first order kinetic model shown lower residual sum of squares (0.0023) than the zero order (0.05873). Hence, shelf life of the jam was calculated using the first order, which can better predict and calculated using the following equation:

$$t_s = \frac{\ln \frac{C_0}{C_e}}{-0.06899}$$

Therefore, when the vitamin C concentration of the jam reduced to the lower amount (high quality deterioration) like 1 mg/100g, its shelf life using the first order will be 27 months.

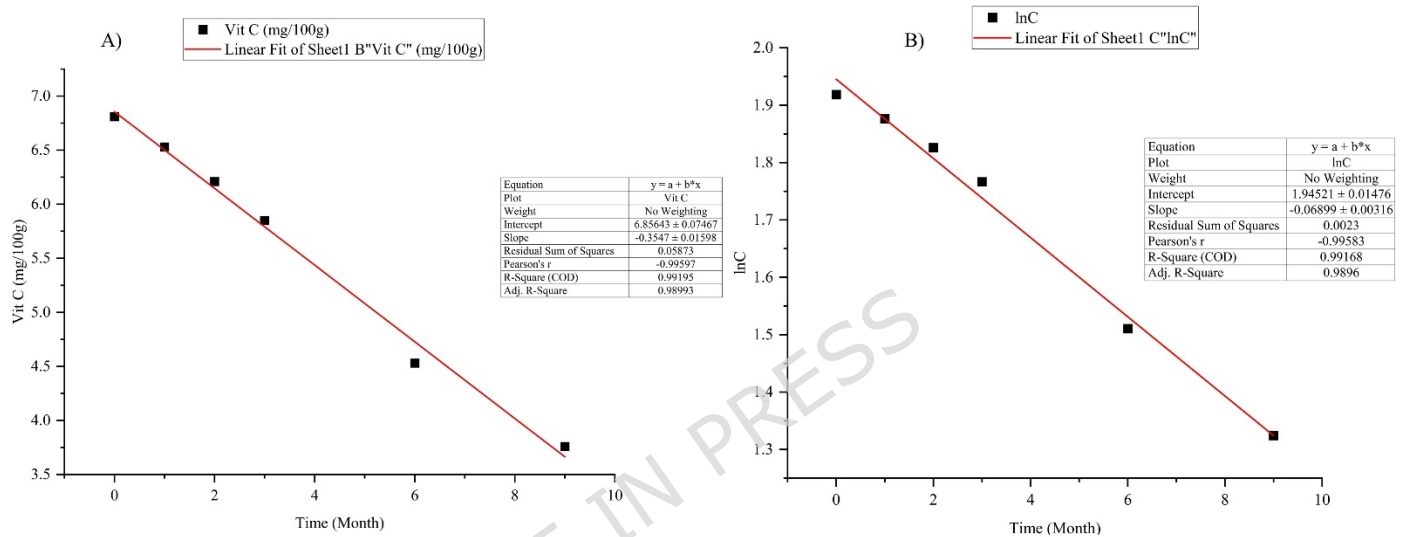


Fig. 5. Shelf life prediction using zero-order (A) and first-order (B) reduction rates of the produced jam stored at room temperature (25°C).

Our observation, predicting the shelf life of the jam produced and stored at room temperature (25 °C) using the first-order kinetic model, is consistent with other reports on fruit jams (Patras et al., 2011; Zaidiyah et al., 2019). For instance, Patras et al. (2011) reported that the degradation of vitamin C (ascorbic acid) in strawberry jam samples stored at 15 °C for 28 days followed first order kinetic model. Although many determining factors are considered, the vitamin C degradation in lingonberry jams was better predicted by the second-order kinetic model than by the zero- and first-order models (Scrob et al., 2022). The difference in storage temperature (25 °C in our study) played a critical role in the vitamin C degradations. Other determining parameter such as oxidation, light sensitivity, oxygen exposure, and the presence of metal ions could be the main factors that lead to vitamin C degradation during

storage (Scrob et al., 2022). There is a scarcity of literature results to compare the produced cactus pear and strawberry fruits blended jam shelf life predicting kinetic models with jams from cactus pear fruit.

4. Conclusion

The knowledge gap and limited technical capacities in cactus pear fruit product development and distribution have been demanding solutions. Moreover, optimizing processing factors such as temperature, time, and blending ratios with other fruits has been demonstrated to improve the quality of fruit jams. In this study, we intend to optimize blended fruit jam processing (temperature, time, and blending ratios), analyze its chemical and microbial qualities, and to predict its shelf-life. Jam production from these blended fruits is promising, which could attract consumers' interest due to the potential nutritional qualities. Hence, a better food value chain could be produced from the perishable cactus pear fruit by developing a jam.

The response surface methodology (RSM) coupled with central composite rotatable design (CCRD) enabled to develop the optimum cooking temperature of 90 °C, time 20 min, and the strawberry fruit blending ratio of 16.9% with a desirability function of 0.84. The blended fruit jam produced at the above-mentioned optimum values of processing showed a titratable acidity (TA) of 1.9 ± 0.12 % citric acid, 58.6 ± 0.72 °Brix total soluble solids (TSS), 6.8 ± 0.51 mg/100g citric acid of vitamin C (Vit C), and 3.2 ± 0.3 of pH value. Shelf life qualities (titratable acidity, total soluble solids, vitamin C, total plate count and yeast and molds) of the produced jam investigated after nine months storage showed slight change. Based on the vitamin C degradation kinetics, the developed first order kinetic model with $R^2 = 0.99168$ demonstrated better shelf life prediction capacity for the produced jam.

Further studies on optimizing the deactivation of enzymes and considering other factors such as concentration of pectin, level of exposure to oxygen, the sources of citric acid, etc. could give better understanding about the cactus pear and strawberry fruit blended jam production. Further studies focusing

on the composition of organic acid and total polyphenol, antioxidant properties, and other characterizations of the jam produced at the developed optimum cooking and blending values could be crucial. Conducting accelerated shelf life prediction of the produced jam, considering vitamin C degradation, could also be helpful.

Author Contributions

Zenebe Tadesse Tsegay: Conceptualization; data curation; methodology; project administration; supervision; formal analysis; investigation; validation; writing original draft. **Mizan Leul:** Conceptualization; project administration; data curation; formal analysis; investigation; validation; writing original draft. **Tesfay Gebregewergis:** Conceptualization; data curation; formal analysis; investigation; validation; writing original draft. **Lijalem Tareke Weldeabezgi:** Supervision; formal analysis; investigation; validation. **Gidey Mehari:** Data curation; formal analysis; investigation; validation; writing original draft. **Teklehaimanot Fisseha Gebremichael:** Data curation; formal analysis; investigation; validation. **Kbrom Abera Seyoum:** Data curation; formal analysis; investigation; validation.

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Plant guidelines: Orange cactus pear (*Opuntia spp.*) from the Kerseber area near Adigrat (Eastern Tigray, Ethiopia) and strawberry (*Fragaria* varieties) from Raya Horti Farm Enterprise (Southern Tigray, Ethiopia) are commercially recognized fruits. The collection and use of these materials complied with the Ethiopian Biodiversity Institute (EBI).

Plant materials declaration: Both plant materials, cactus pear fruit (*Opuntia spp.* variety) and strawberry fruits (*Fragaria* variety) collected and utilized in this research work followed local agricultural guidelines and institutional research protocols. No protected or endangered plant species were involved in this research.

Data Availability Statement: Data will be made available on request.

Declaration Section

Ethics Statement: This study does not involve any human or animal testing.

Conflicts of Interest: The authors declare no conflicts of interest.

Consent to Participate: Not applicable.

Clinical trial number: Not applicable.

Consent to publish: Not applicable.

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