

Sustainable Food Technology

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: V. Challana, A. Naykodi, A. K. Sahoo and S. Shirkole, *Sustainable Food Technol.*, 2025, DOI: 10.1039/D5FB00788G.



This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the [Information for Authors](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the [Ethical guidelines](#) still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.

Sustainability Spotlight:

This research advances sustainable food preservation by optimizing UV-C irradiation as a non-thermal method for enhancing the microbial safety and quality of Kinnow fruit juice. By reducing microbial load and maintaining vitamin C content without the use of heat or chemical preservatives, the process offers an energy-efficient and environmentally friendly alternative to conventional thermal pasteurization. The integration of modeling tools such as RSM and ANN ensures process precision, while shelf-life evaluation under refrigerated storage demonstrates extended product stability by nearly six days, effectively reducing post-harvest and processing losses.

Through improved resource efficiency, waste reduction, and adoption of low-energy technologies, this study contributes to **SDG 2** (Zero Hunger) by promoting food availability through longer shelf life, **SDG 9** (Industry, Innovation, and Infrastructure) by applying innovative non-thermal and data-driven processing approaches, and **SDG 12** (Responsible Consumption and Production) by encouraging sustainable food manufacturing practices that minimize environmental impact.



ARTICLE

Optimizing UV-C for Microbial Safety and Quality of Kinnow Fruit Juice

Vimal Challana,^{*a} Ankita Naykodi,^a Shivanand Shirkole,^{a,b} and Akshaya K. Sahoo^{*a}Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

The study analyzed UV-C irradiation as a non-thermal preservation method for Kinnow fruit juice (KFJ), aiming to reduce microbial contamination while preserving vitamin C content. By eliminating the need for thermal processing and chemical preservatives, the approach promotes energy-efficient and environmentally sustainable juice preservation. Using Response Surface Methodology (RSM), optimal UV exposure (25 minutes at 5 cm) predicted 34.056% vitamin C loss and 3.539 and 3.485 log reductions of AM and YM, respectively. The ANN model demonstrated superior performance over RSM, indicating that ANN gives more accurate and reliable predictions. First-order kinetic modeling ($R^2 = 0.983$) shows better fittings than the Weibull model. Shelf-life studies revealed that KFJ stored at 4 °C in glass containers retained higher vitamin C and microbial stability, extending product shelf-life by nearly 6 days. These findings suggest that UV-C processing, in combination with proper packaging and storage conditions, holds the potential for juice preservation at the commercial level.

Keywords: Ultraviolet, Shelf-life, Kinnow fruit juice, Vitamin C, Yeast and mold, Aerobic mesophiles

^a Department of Food Engineering and Technology, Institute of Chemical Technology Mumbai, ICT-IOC Campus, Bhubaneswar, 751013, India.

^b Department of Food Technology, School of Engineering and Technology, D. Y. Patil Agriculture and Technical University, Talsande, Kolhapur, 416112, India

* Corresponding Author: Akshaya K. Sahoo (ak.sahoo@iocb.ictmumbai.edu.in); Vimal Challana (vimalchallana@gmail.com)



ARTICLE

1. Introduction

Kinnow is a cross between 'King' (*Citrus nobilis*) and 'Willow Leaf' mandarin (*Citrus deliciosa*) that belongs to the *Rutaceae* family and is extensively cultivated in India and Pakistan. According to the Department of Agriculture & Farmers Welfare ¹, citrus fruit production in India reached 14.81 million metric tonnes, with cultivation over 1.095 million hectares. Major citrus fruits grown in India include Kinnow, Mosambi, Orange, Lemon, Lime, Grapefruit, tangerine, and galgal, mainly suitable for Southeast Asia agro-climatic conditions. In India, its production is mainly in the regions such as Punjab, Rajasthan, Himachal Pradesh, Jammu & Kashmir, Haryana, and Uttarakhand. Kinnow—a hybrid mandarin variety—is extensively cultivated in Punjab, with annual yields reaching 1.2 million metric tonnes. Kinnow is recognized by medium-sized, oblate fruits with smooth, glossy orange skin and deep orange flesh ^{2,3}. The fruit is highly cherished for its pleasant flavor, vibrant color and therapeutic properties. Kinnow fruit consists of components such as flavedo, albedo, seeds and juice sacs (present in segments).

Kinnow is a seasonal fruit harvested from mid-December to mid-March, with peak yield in January and February. Kinnow fruit grows best under temperatures of 10-35 °C, annual rainfall of 500-1200 mm, moderate humidity levels (60-70 %), and 6-8 hours of daily sunlight. However, the abundance of fruit during this period results in significant post-harvest losses if not managed properly. Due to its high water content, Kinnow is highly susceptible to microbial attacks ⁴. Harvest and post-harvest losses of Kinnow account for 25-30% ⁵.

Various processing techniques, such as ultrafiltration, can be employed to minimize the losses and extend its availability ⁴. Kinnow juice is a primary processed product from a ripened fruit rich in vitamin C, folate, provitamin A, and other nutrients, such as asparagine, arginine, aspartic acid, proline and glutamine-like amino acids. It also provides essential minerals, meeting the body's calcium, magnesium, phosphorus, manganese, iron, zinc, and copper requirements. Moreover, the juice is abundant in bioactive components like phenols, flavones, flavonoids, limonoids, along with carotenoids, which can contribute to its health benefits ⁶. The juice from the Kinnow fruit can be extracted using hand-reaming and mechanical juice extractors. The extracted Kinnow fruit juice (KFJ) can be consumed in its natural or raw state and processed for extended shelf-life and numerous applications. KFJ is easily prone to microbial spoilage, which can limit its market value due to its limited shelf life. For enhancing the safety and stability of KFJ, it is crucial to eliminate both microbes and inherent enzymes. The presence of inherent enzymes can result in loss of color, flavor, texture and nutrients in Kinnow.

Microbial growth and enzymatic activity play an important role in the spoilage of fruit juices, mainly due to aerobic mesophiles (AM), yeasts, and molds (YM). Both conventional and emerging preservation techniques have been assessed to address this issue. Studies have reported the use of ohmic heating, pasteurization ⁷ and

combinations involving preservatives ^{8, 9}, ultrafiltration ⁴, and ozonation ^{10, 11} in maintaining the juice quality. While thermal treatments effectively can inactivate spoilage organisms, they often come at the cost of reduced nutritional and sensory attributes. In contrast, non-thermal treatments preserve these qualities, which makes them a preferable alternative for juice stabilization. In the era of novel non-thermal preservation techniques, ultraviolet (UV) irradiation stands out as an effective and promising method for preservation. UV treatment provides microbial safety and helps in retaining nutritional and sensory attributes, making it a low-energy, cost-effective alternative to conventional thermal methods without using preservatives ¹². Very limited literature is available on traditional heat treatment and non-thermal techniques like UV processing for KFJ.

The mechanism of microbial inactivation is associated with UV light through multiple pathways. DNA damage is the primary cause behind microbial cell inactivation, while lipid peroxidation and protein denaturation contribute to the same. UV-C radiation induces thymine-thymine dimer formation, which can alter the bioactive properties of microbial cells. In addition, UV-C generates cyclobutane-pyrimidine dimers with cytotoxic effects and 6-4 photoproducts, which are highly lethality and mutagenic. Reactive oxygen species produced during UV treatment can lead to lipid oxidation, disrupting the lipid bilayer by forming pores and disintegrating the membrane. The treatment induces oxidative changes in amino acids, resulting in conformational and compositional changes that inhibit critical enzymes and disrupt cellular functions ¹³. Figure 1 illustrates the mechanism behind microbial inactivation by UV light.

This study evaluates the impact of UV and thermal treatments on the quality characteristics of KFJ during storage. The juice was packaged in glass (GS) and polyethylene terephthalate (PET) and stored at two different temperatures (4°C and room temperature). The key parameters, like ascorbic acid and microbial load, were evaluated to assess the quality degradation over storage time.

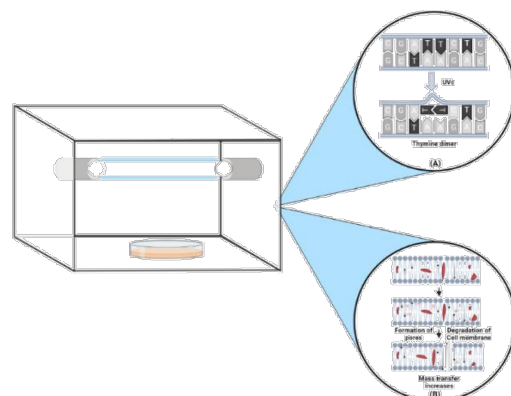


Figure 1: Mechanism behind the inactivation of microbes by UV lamp



2. Materials and Methods

2.1 Kinnow Juice Preparation

Fresh and ripe Kinnow fruit was bought from the local market in Bhubaneswar, Odisha, India. The fruits underwent cleaning and sorting, before storing the fruit at 4°C until further analysis. The fruit peel was removed using a sanitized stainless-steel knife. The albedo portion was removed manually to separate the edible segments before juice extraction. The KFJ was extracted using a multifunctional food processor (Bajaj Electricals Limited, Model: FX11 600 Watts Food Processor). After extraction, the juice underwent filtration thrice using three-layered cheesecloth to separate juice from larger pulp particles and seeds.

2.1 Description of the Ultraviolet treatment system

The UV chamber was designed to provide uniform exposure to UV rays. The system consists of a cuboid closed chamber constructed from 20 mm white acrylic sheets, chosen for their durability, ease of cleaning, and high visibility to detect stains or spilled juice, which can aid in sterilization and contamination prevention. The chamber dimensions are 48 cm in length, 15 cm in breadth, and 24 cm in height (Figure 2). A UV-C lamp (GHO436T5L, Arklite Specialty Lamps Pvt. Ltd., India) of 48 W power was installed inside the chamber. The distance between the juice and the lamp can be regulated through a movable base, ensuring consistent UV exposure to the KFJ. To uphold sterile conditions, the chamber was sanitized with 80% ethanol before any experimental run. The operation of the lamp was controlled manually using a switch and stopwatch to ensure accurate treatment durations.

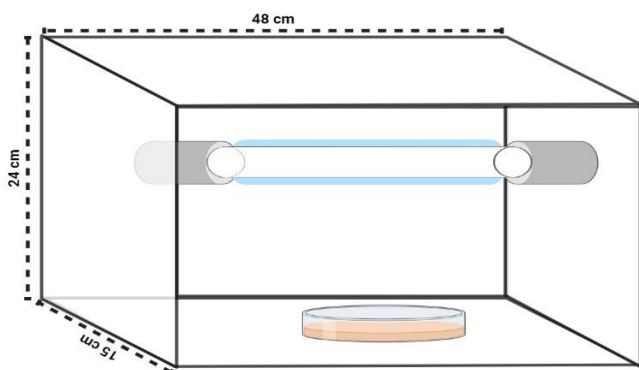


Figure 2: Designed ultraviolet system

2.2 Experimental design and optimization

A face-centered central composite design optimized UV treatment conditions for maximum microbial reduction and minimizing vitamin C loss. The distance between the lamp and juice (Y_1) and treatment time (Y_2) were independent variables. In contrast, dependent variables assessed during the experiment design were total plate count (log reduction), Yeast and Mold (log reduction), and percentage loss of vitamin C. Independent parameters were evaluated at three distinct levels: distance at 3, 5, and 7 cm and treatment time at 15, 20, and 25 min. UV intensity was maintained constant throughout the experiment due to operational limitations of the UV system used; therefore, it was not included as an independent variable in the optimization study. The independent parameter limits were determined through preliminary trials. The experimental design and data analysis used Design-Expert software

(version 13, Stat-Ease Inc., USA). 13 experimental runs were obtained, including 8 factorial runs, which represent different combinations of independent parameters, and 5 replicates at the center point to assess experimental error and ensure the results reproducibility.

2.3 Thermal treatment

Thermal treatment (TT) was conducted using a water bath (Meta Lab Scientific Industries Ltd., Mumbai, India). The KFJ sample was transferred to sterile stainless-steel containers covered with lids. The containers were placed in a preheated water bath at 90 °C. The KFJ was held at 90 °C for 2 minutes after the temperature reached 90 °C. After pasteurization, the juice was immediately cooled to room temperature by immersion in an ice bath. The juice was transferred to GS and PET bottles in a sterile environment.

2.4 Enumeration of microbial population

The AM and YM microbial populations in the KFJ were enumerated using the serial dilution-pour plate method. Fresh, UV and TT-treated KFJ samples were diluted with sterilized saline water (0.85% w/v sodium chloride in distilled water)¹⁴. The prepared dilutions were transferred 1 mL of diluted inoculum to a sterile petri plate, and 10-12 mL of agar was added. The Petri plate was rotated gently to ensure uniform mixing before the agar solidified. A second layer of 8-10 mL agar was poured to complete the plating process. Nutrient agar (HIMEDIA® M001-500G) was used for AM, while Potato dextrose agar (HIMEDIA® M096-500G) was used for YM. The petri plates were incubated for 24-36 hours at 37 °C for AM, while YM were incubated at 30 °C for 3-5 days. AM and YM can be expressed as colony-forming units per milliliter (CFU/mL). The reduction in microbial load can be calculated in the form of log cycles using the following equation.

$$n = \log\left(\frac{N_0}{N}\right) \quad (i)$$

Where n represents the log cycle reductions, N_0 is the initial microbial count in untreated KFJ (CFU/mL), and N is the microbial count in treated KFJ (CFU/mL)⁷.

2.5 Vitamin C

Vitamin C was determined spectrophotometrically using 2,6-dichlorophenolindophenol at 518 nm, in accordance with Challana *et al.*¹⁵. The ascorbic acid content was expressed as milligrams per 100 mL of juice (mg AA/100 mL).

2.6 Artificial neural network

2.6.1 Artificial neural network modeling

For developing and assessing different Artificial Neural Network (ANN) models, MATLAB software (R2018a, MathWorks, USA) was employed to validate the responses obtained from RSM. There are three layers on the ANN surface, i.e., input, hidden, and output. These were constructed using a feed-forward topology. The input layers consist of two independent variables: distance between the lamp and juice and treatment time, with Total Plate Count (log reduction), Yeast and Mold (log reduction), and percentage loss of vitamin C considered as output-dependent variables (Figure 3).



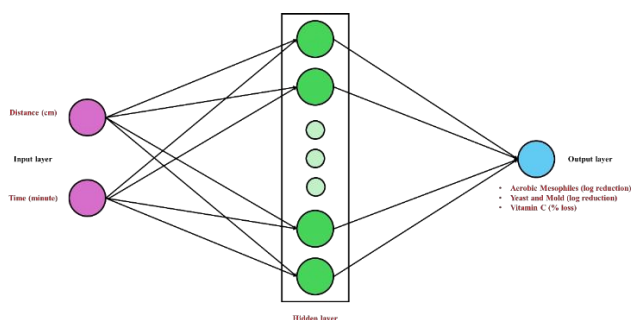


Figure 3: ANN model configuration

The number of neurons in the hidden layer was determined through a trial-and-error approach to optimize network performance. The number of neurons varied from 1 to 20. A small number of neurons could result in underfitting, whereas excessive neurons can cause overfitting and prolong the training time. Before splitting the dataset into training (70%), validation (15%), and testing (15%) subsets, the datasets underwent randomization to ensure a representative distribution. The available dataset consists of 13 observations per variable, constrained by experimental data availability. To address these constraints and strengthen the model validation, a k-fold cross-validation strategy was employed. The strategy ensured that each data point contributed to training and testing, which can help overcome the effects of limited datasets and enhance the model's reliability and prediction accuracy. A comparative analysis was conducted between the ANN and RSM models to assess better fitting, predictive capability, and accuracy^{15, 16}.

2.6.2 Comparison between RSM and ANN models

The different statistical indices like the coefficient of regression (R^2), mean square error (MSE), and root mean squared error (RMSE) were used to evaluate the performance of the ANN model^{15, 17}. The statistical parameters were analyzed using the following equations.

$$MSE = \frac{1}{n} \sum_{j=1}^n (Y_j - \hat{Y}_j)^2 \quad (ii)$$

$$RMSE = \left\{ \frac{1}{n} \sum_{j=1}^n (Y_j - \hat{Y}_j)^2 \right\}^{1/2} \quad (iii)$$

$$R^2 = \frac{\sum_{j=1}^n (Y_j - \hat{Y}_j)^2}{\sum_{j=1}^n Y_j^2 - \sum_{j=1}^n \hat{Y}_j^2} \quad (iv)$$

where n is the observation number, Y_j is the predicted output variable for the i^{th} observation, and \hat{Y}_j is the experimental output variable for the i^{th} observation.

2.7 Curve Fitting for microbial inactivation

Microbial inactivation during UV treatment was described using first-order kinetics and the Weibull model.

2.7.1 First-Order Kinetics

Microbial reduction followed by first-order kinetics can be expressed using equation (v). This model can be applied only when the microbial reduction increases proportionally with treatment intensity.

$$\log\left(\frac{N_i}{N_t}\right) = kt \quad (v)$$

N_i is the initial microbial count (CFU/ mL), N_t is the microbial count after treatment time t , and k is the first-order inactivation rate constant (s^{-1}).

2.7.2 Weibull Model

The Weibull model can be applied to the non-linear microbial inactivation, which can be described by the equation (vi)

$$\ln\left(\frac{N_i}{N_t}\right) = \left(\frac{t}{\delta}\right)^\beta \quad (vi)$$

where N_i is the initial microbial count (CFU/ mL), N_t is the microbial count after treatment time t , δ is the scale parameter (characteristic time), and β is the shape parameter¹⁸.

β is the deciding factor for the Weibull distribution curve. If:

- $\beta < 1$ represents upward concavity, indicating microbial resistance and adaptation to UV stress over time.
- $\beta > 1$ represents downward concavity, suggesting accelerated microbial inactivation and increasing susceptibility with prolonged UV treatment.
- $\beta = 1$ represents a linear curve and reflects a constant microbial inactivation rate where the microbial inactivation is independent of exposure duration.

2.8 Shelf-life estimation

PET and GS bottles were the two packaging materials for storing and processing. A storage analysis was performed for fresh, UV, and TT samples (JU and JT), with a primary focus on ensuring the microbiological safety of KFJ. The KFJ samples were unacceptable if the microbial count exceeded 6 log counts¹⁹. **Fresh samples (untreated juice), UV-treated samples, and thermally treated (TT) samples were analyzed after 48 hours to evaluate the effect of different treatments. Fresh samples refer to untreated juice with no processing applied. UV-treated samples were those exposed to the optimized UV treatment conditions determined in this study. Thermally treated (TT) samples were processed at 90 °C for 2 minutes prior to storage.** The shelf-life was determined by evaluating the critical parameters such as AM, YM, and vitamin C.

Table 1. Actual values and coded values for the factors that are variable, and experimental values of responses collected during UV using FCCD

Run	Factor 1	Factor 2	Response 1	Response 2	Response 3
	Distance	Time	Aerobic mesophiles	Yeast and Mold	Vitamin C
	[cm]	[minute]	[log reduction]	[% loss]	[% loss]
	A	B	Y_1	Y_2	Y_3
1.	7	15	2.279	2.159	21.842
2.	5	20	3.169	2.987	32.554
3.	7	25	2.371	3.415	25.127
4.	5	20	3.315	3.214	29.895
5.	5	15	2.314	2.359	29.639
6.	5	20	3.478	3.150	30.588
7.	7	20	2.314	2.987	27.856
8.	3	15	3.059	2.538	38.430



9.	5	25	3.812	3.536	34.295
10.	5	20	3.515	3.090	27.845
11.	3	20	3.840	3.369	43.799
12.	3	25	3.989	3.599	50.235
13.	5	20	3.418	2.895	31.114

3. Results and Discussion

3.1 Effect of independent parameters on responses

The effect of independent variables and their interactions on dependent variable observations is provided in Table 1. The fresh KJF has an AM count of 4.38 log CFU/ mL, a YM count of 5.12 log CFU/ mL, and a vitamin C concentration of 35.65 ± 2.75 mg of ascorbic acid/100 mL.

3.1.1 Aerobic Mesophiles

The actual values and coded values of the independent variables, along with the responses, are given in Table 4. The log reduction value of AM varies from 2.28 to 3.99 across the different experimental conditions. Based on the ANOVA results (Table 2), the model's overall F-value is 13.09 and has a *p*-value of 0.002, which signifies that the model is statistically significant. The model has an R² value of 0.903, which means that there is a 90.3% variability in AM reduction that the model can explain. There was a non-significant lack of fit, suggesting that the model accurately predicts the AM. The factors, i.e., distance (A) and time (B), significantly impact AM reduction. Whereas AB, A² and B² are factors that do not substantially alter the AM count reduction.

Equation (vii) gives the correlation between the AM log reduction and independent parameters

AM (log reduction)

$$= + 3.36 - 0.654 A + 0.42 B - 0.21 AB - 0.223 A^2 - 0.237 B^2 \quad (\text{vii})$$

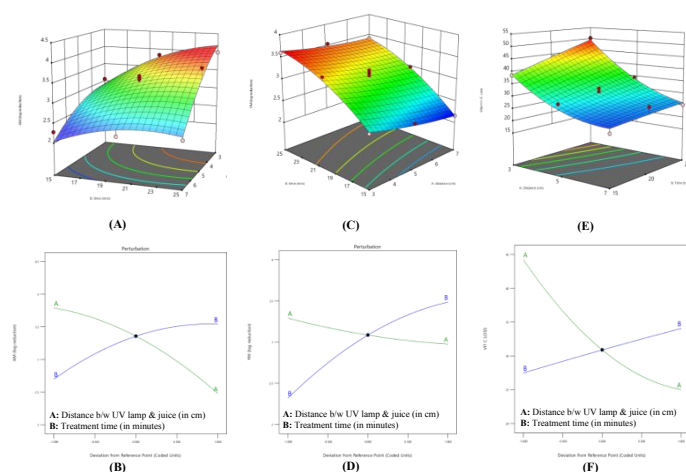


Figure 4: Response surface plots (A, C, E) and perturbation plots (B, D, F) depicting the effect of independent parameters after UV treatment on (A, B) Total plate count log reduction; (C, D) Yeast and mold log reduction; (E, F) vitamin C loss.

From the above equation, the negative coefficient of distance suggested that distance and reduction in AM are inversely proportional to each other, which means a decrease in distance between the UV lamp and KJF resulted in higher AM count reduction (Figure 4 (A and B)). Similarly, the positive coefficient of time suggests that exposure time is directly linked with a reduction in AM count. The trends align with the findings reported by Kim *et al.*²⁰, where reducing the sample's distance from the UV lamp and increasing the exposure time resulted in improved microbial reduction in lettuce. The trend could be ascribed to an increase in the distance, resulting in a lower intensity of UV, which diminished the antimicrobial effect, while prolonged treatment enhances the antimicrobial impact. The decrease in effectiveness with longer distances can be explained by the "inverse square law," which states that doubling the distance resulted in a four-fold decrease in irradiance^{21, 22}. As UV intensity diminishes with distance, prolonged treatment is required to achieve the same effect as at a closer distance.

3.1.2 Yeast and Mold

YM value varied from 2.16 to 3.6 log reduction (Table 1). Based on the ANOVA results (Table 2), the model value was found to be highly significant (*p* < 0.0001) with an R² value of 0.966, which depicts 96.6% variability in the data. The lack of fit was non-significant, which confirmed that the model adequately describes the data. The factors A, B and B² have been found to have a significant (*p* < 0.05) influence on the reduction of YM. At the same distance and time, other factors like AB and A² are found to be statistically insignificant (*p* > 0.05).

The correlation between YM reduction and independent parameters is given below:

YM (log reduction)

$$= + 3.09 - 0.158 A + 0.582 B + 0.049 AB + 0.048 A^2 - 0.183 B^2 \quad (\text{viii})$$

From the above equation, the negative coefficient indicates that reducing the gap between the UV lamp and KJF enhances YM reduction, demonstrating an inverse relationship as illustrated in Figures 4 (C and D). On the other hand, the positive coefficient of time suggested that longer exposure leads to a higher YM reduction. The negative coefficient of B² indicates that while increasing treatment time improves the YM reduction, the effect decreases after a certain time, indicating a plateau or decline in effectiveness with longer exposure.

The reduction in YM is less pronounced than AM, indicating UV treatment is more effective against AM, which can be attributed to the reduced pyrimidine nucleosides (cytosine and thymine) in YM genetic material, along with the thicker cell wall of the YM in comparison to AM^{23, 24}. These factors contribute to the higher resistance of yeast cells to UV treatment. Similar findings were reported by Torkamani and Niakousari²⁵ in UV-treated orange juice, where bacteria were more affected than YM. This was likely due to their smaller size, simpler cell wall composition, and higher pyrimidine content, resulting in bacterial DNA being more prone to UV-induced damage.

3.1.3 Vitamin C

Vitamin C loss after treatment ranged from 21.84 to 50.23% (Table 1). The ANOVA results (Table 2) indicate that the model was found to be statistically significant (*p* < 0.01). The distance plays a dominant



role over exposure time in contributing to the % vitamin C loss during UV treatment. The quadratic model fits the vitamin C loss well, demonstrating no significant lack of fit, which is desirable for evaluating the impact of independent variables. The model's R^2 value was 0.956, which signifies strong predictive accuracy. The correlation between % vitamin C loss and independent parameters is given below:

% Vitamin C loss

$$= + 30.88 - 9.61 A + 3.29 B - 2.13 AB + 3.75 A^2 - 0.116 B^2 \quad (\text{vi})$$

The perturbation plot (Figure 4 (F)) highlights that distance was found to have a greater influence on vitamin C degradation than exposure time. The plot clearly illustrates that increasing the distance between the UV lamp and the sample reduces the vitamin C loss as the effectiveness of UV reduces with an increase in the gap. On the other hand, longer treatment time was directly linked with higher vitamin C degradation. The positive coefficient of A^2 indicates an inverted parabolic response, which means the loss of vitamin C initially increases with an increase in distance, but beyond a certain limit, the loss of vitamin C decreases.

Spectrophotometric analysis of KFJ (Fig. 5) revealed maximum absorption peaks mainly in the UV region (200-400 nm), with minimal absorption beyond 400 nm in the visible spectrum, which signifies that most of the light is transmitted in the visible range. This suggests that vitamin C degradation is more rapid in the UV region, with minimal impact from visible light. Similar findings were observed by de Souza *et al.*²⁶, which reported a decrease of nearly 23% in vitamin C content in citrus juice after UV-C treatment. The degradation could be attributed to the absorbance of ascorbic acid near 260 nm, which overlaps with the UV-C region, thereby accelerating its degradation. As vitamin C is very sensitive to light and temperature²⁷, prolonged exposure to UV accelerates its degradation when the distance between the juice and the minimum distance to the higher intensity of UV light results in more significant vitamin C loss.

Table 2. Summary of the estimated coefficients of the quadratic model for dependent variables

Factors	Aerobic Mesophiles [log reduction] (Y_1)		Yeast and Mold [log reduction] (Y_2)		Vitamin C Online [% loss] (Y_3)	
	Coeff.	p-Value	Coeff.	p-Value	Coeff.	p-Value
Intercept	3.356		3.085		30.880	
A	-	<	-	0.009	- 9.607	<
	0.654	0.001	0.158	a	a	0.001
B	0.420	0.005	0.582	<	3.291 ^a	0.065
	a	a	a	0.001	a	a
AB	-	0.145	0.049	0.393	- 2.13 ^b	0.083
	0.210	b	b	b	b	b
A^2	-	0.190	0.048	0.483	3.745 ^a	0.021
	0.223	b	b	b	a	a
B^2	-	0.167	-	0.025	- 0.115	0.930
	0.237	b	0.183	a	b	b
Lack of fit	not significant		not significant		not significant	
ANOVA of the model						
F-values	13.09		39.90		30.61	
p-value (model)	0.002		< 0.0001		0.001	
p-value (LOF)	0.052		0.817		0.238	
R^2	0.903		0.966		0.956	

Superscript a represents a p -value less than 0.05 ($p < 0.05$), whereas superscript b represents a p -value greater than or equal to 0.1 ($p \geq 0.1$)

The results show that distance is important in microbial inactivation and vitamin C retention. The increase in distance resulted in lower microbial inactivation but also helped in better retention of vitamin C. Whereas the increase in treatment time improved the microbial inactivation and diminished the vitamin C concentration. These responses indicate an inverse relation between nutrient retention and microbial inactivation. Torkamani and Niakousari²⁵ also reported that enhancing UV-C treatment resulted in microbial reduction but also caused loss of vitamin C. These findings highlight the inverse relationship between microbial load and nutrient retention.

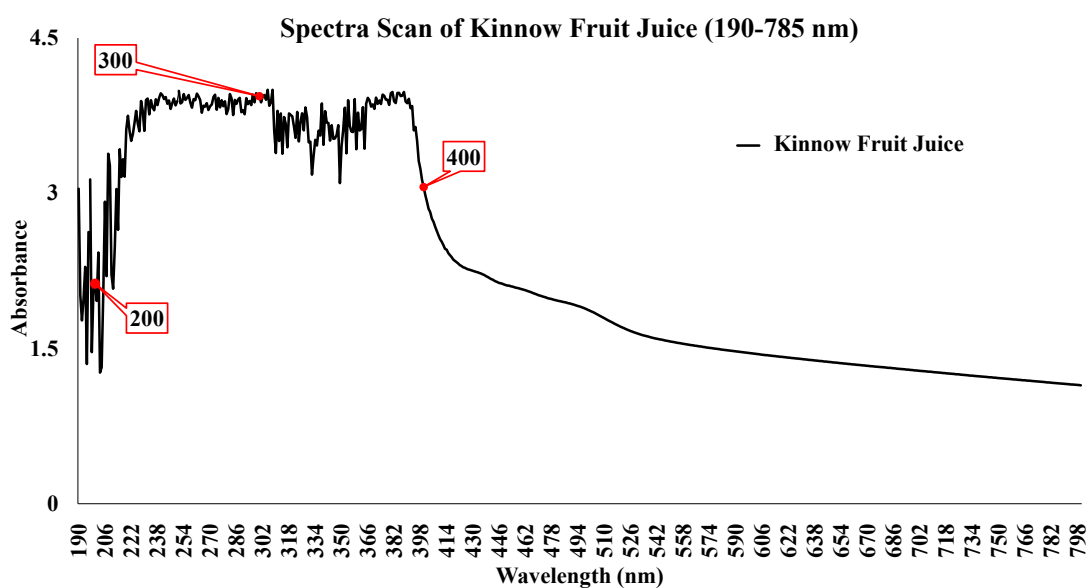


Figure 5: Spectra Scan of Kinnow fruit juice (190-785 nm)**3.1.4 Optimization of Ultraviolet treatment as a non-thermal technique for preservation**

After conducting RSM, numerical optimization was performed to maintain the desired balance between microbial safety and vitamin C retention. The goal was to minimize the vitamin C loss to maintain nutritional value while maximizing the log reduction value of AM. For the YM reduction, no specific preference was set.

The relative importance (*r*) values were assigned to prioritize the outcomes; *r* = 5 was set to minimize the vitamin C loss, and *r* = 3 was set to maximize AM reduction. The overall desirability value (*D*) was used to evaluate the fitness of each solution. The higher *D* value means closer alignment with the desired objectives. The solution yielding the highest *D* value was selected. The optimized conditions were 5 cm distance between juice and UV lamp and 25 minutes exposure time with a *D* value of 0.826. The predicted responses were 34.056% vitamin C loss, 3.539 log reduction of AM, and 3.485 log reduction of YM. Hagkuder Taze *et al.*²⁸ reported that the UV-treated

The experimental values for the log reduction of AM and YM were 3.311 ± 0.186 (93.56%) and 3.220 ± 0.170 (92.37%), respectively. Similarly, vitamin C loss was observed at $30.874 \pm 0.657\%$, with an accuracy of 90.66%. Validation of responses under optimized conditions is presented in Table 3. These results confirm the reliability of the predictive models used for process optimization. Minor deviations between predicted and experimental values were within acceptable limits for practical applications.

3.2 Artificial neural network**3.2.1 Artificial neural network modeling**

A multi-layer feed-forward topology ANN was used, and different configurations were estimated by varying the number of neurons. The MSE of the output layer was plotted against the varying neuron counts. This analysis demonstrated the impact of a hidden number of neurons on network performance²⁹. The optimal models were determined based on the lowest MSE and highest *R*², which were identified as 2-15-1 for AM, 2-9-1 for YM, and 2-13-1 for vitamin C loss (Figure 6).

Figure 7 (A-C) illustrates the ANN model's training progress, including MSE across training, validation and test data sets over the 7 epochs for AM, 20 for YM, and 13 for vitamin C loss. The best validation performance was observed with MSE values of 0.0202 (at epoch 1) for AM, 0.0199 (at epoch 16) for YM, and 7.431 (at epoch 7) for vitamin C loss. An overview of the training process for all models is illustrated in Figure 7 (D-F). The ANN-predicted correlation coefficients (*R*) for the training, validation and testing phases were 0.9838, 0.8166, and 0.9897 for AM; 0.9668, 0.9631, and 0.9736 for YM; and 0.9108, 0.9880, and 0.9951 for vitamin C loss, respectively (Figure 7 (G-I)).

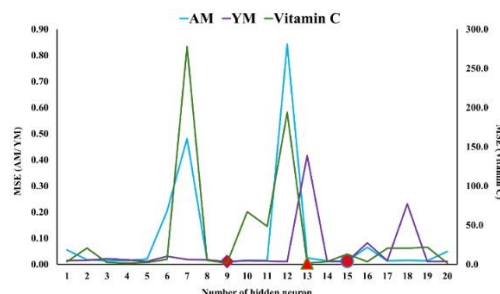
orange juice at an intensity of 1.32 mW/cm² for 20 minutes resulted in a YM reduction of 1.76 log count at a dose of 108.42 mJ/cm².

Table 3. Validation of response, i.e., % increase in yield and % loss of vitamin C of KFJ at optimized conditions

Optimized Process	Predicted ^a	Experimental ^b	Accuracy (%)
Aerobic mesophiles [log reduction]	3.539	3.311 ± 0.186	93.56
Yeast and mold [log reduction]	3.485	3.219 ± 0.168	92.37
Vitamin C [% loss]	34.056	30.874 ± 0.657	90.66

^a predicted value of dependent parameters with the help of quadratic equations

^b data is the average of 6 experiments at the expected optimum conditions of the independent variables

**Figure 6:** Comparison of ANN performance based on the least RMSE values for AM, YM (log reduction), and vitamin C loss with different hidden neuron numbers.**3.2.2 Comparison of RSM and ANN Models**

The predictive performance of RSM and ANN models for AM and YM (log reduction) and % vitamin C loss was compared using statistical parameters such as MSE, RMSE and *R*² values, as presented in Table 4. The results demonstrated that ANN outperformed RSM for AM and vitamin C loss parameters. For AM, the ANN model has lower MSE (0.012) and RMSE (0.110) in contrast to RSM (MSE: 0.035, RMSE: 0.187) with a higher *R*² value (0.967), which indicates more reliable and precise predictions of the model. In addition to vitamin C loss, ANN gives better results with reduced MSE (1.470), RMSE (1.210), and a higher value of *R*² (0.973), which demonstrates better modeling of quality degradation.

Although the RSM model showed a marginal advantage in predicting YM (log reduction), it had a lower MSE (0.006) and RMSE (0.079). In addition, the ANN model maintained a strong *R*² value (0.946 vs. 0.966), which signifies that ANN is still a reliable approach. It can be concluded that the ANN model demonstrated superior performance in handling complex, non-linear associations³⁰ and offers enhanced predictive accuracy for microbial and quality parameters, and RSM is limited to second-order polynomial approximations.



ARTICLE

Sustainable Food Technology Accepted Manuscript

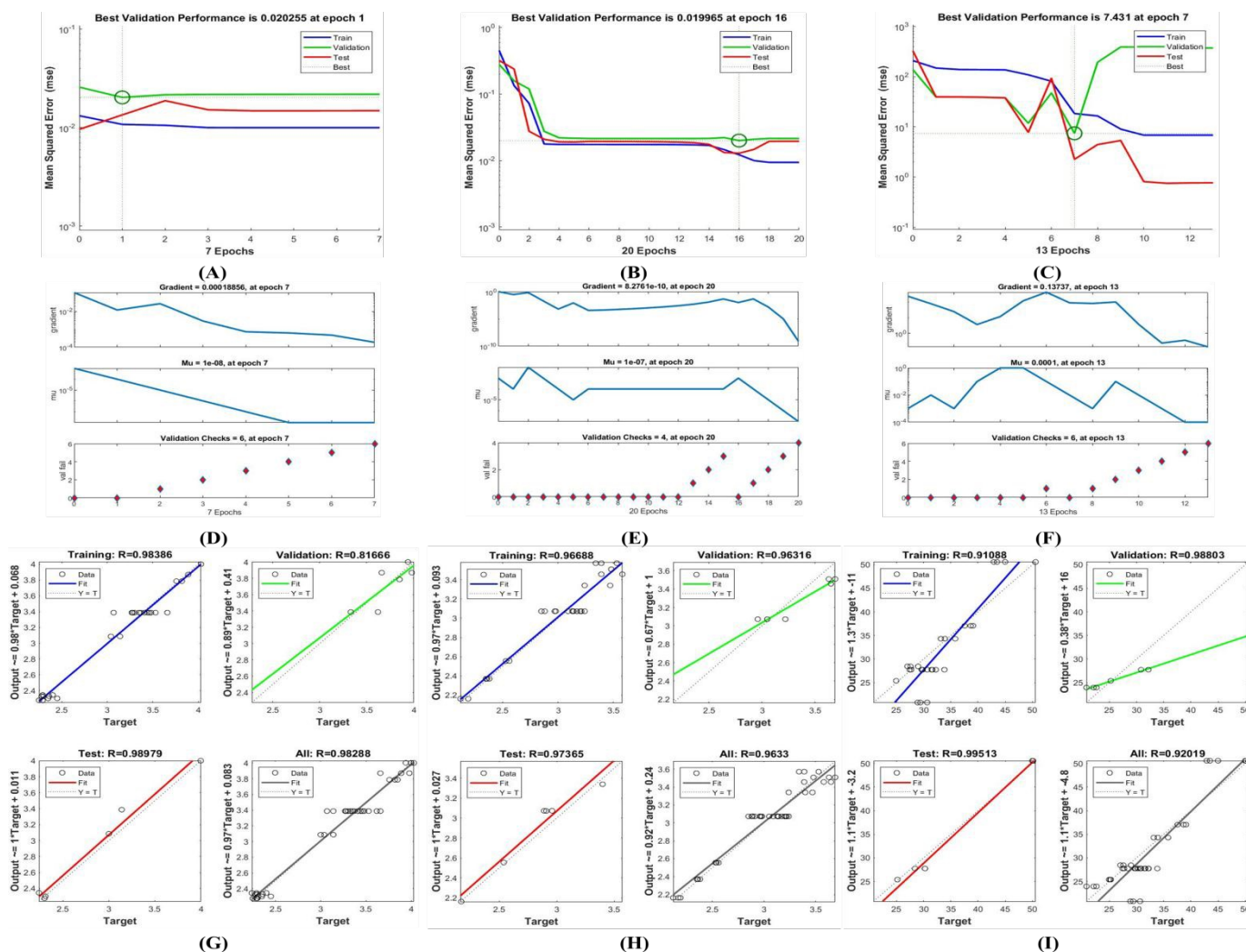


Figure 7: Training and performance evaluation of the ANN model for (A) AM log reduction, (B) YM log reduction, and (C) % vitamin C loss, with corresponding performance plots (D–F) and comparison between experimental and predicted (G–I).

Table 4. Predictive accuracy comparison between RSM and ANN for model outputs

Parameters	AM (log reduction)		YM (log reduction)		% Vitamin C loss	
	RSM	ANN	RSM	ANN	RSM	ANN
MSE	0.035	0.012	0.006	0.010	2.400	1.470
RMSE	0.187	0.110	0.079	0.101	1.549	1.210
R ²	0.903	0.967	0.966	0.946	0.956	0.973

3.3 Microbial Inactivation Modeling for Ultraviolet Treatment

The microbial inactivation modeling for UV treatment was estimated using first-order kinetics and the Weibull distribution model. Table 5 shows that the first-order kinetics model ($R^2=0.983$) fits better than

Open Access Article. Published on 22 April 2026. Downloaded on 4/23/2026 12:40:57 AM. This article is licensed under a Creative Commons Attribution-NonCommercial 3.0 Unported Licence.



the Weibull distribution model ($R^2=0.979$). The inactivation rate constant (k) for first-order kinetics was determined as 0.108, suggesting a steady microbial inactivation over time. In the Weibull distribution model, α (the scale parameter) was 14.14, and β (the shape parameter) was 1.403. The $\beta > 1$ predicts downward concavity, suggesting accelerated microbial inactivation and increasing susceptibility with prolonged UV exposure. This suggests that the microorganisms become more vulnerable with time when exposed to UV due to cumulative damage induced by UV light. Both models effectively describe the inactivation of microbes, but the Weibull model provides an extra edge in varying resistance patterns.

Table 5. R^2 value and constant values of both the model's first-order kinetics and the Weibull model

Parameters	First-order kinetics	Weibull distribution model
R^2	0.983	0.979
Equation	$y = -kx$	$y = -(x/\alpha)^\beta$
Parameters	$k = 0.108$	$\alpha = 14.14$ $\beta = 1.403$

3.4 Shelf-life

3.4.1 Effect on microbial quality during storage

The AM and YM are the naturally occurring microflora commonly present in fruit juices and have been recognized as the main contributors to spoilage and decreased shelf-life³¹. So, maintaining microbial stability is a key requirement for maintaining the safety and quality of fruit juices during storage. The maximum allowable limit for AM or YM counts in acidic fruit juice and purees should not exceed 6.0 log CFU/mL³². The microbial stability of control, thermally treated, and UV-treated KFJ stored in glass and PET bottles under refrigerated (4 °C) and room temperature conditions were monitored to assess the shelf-life of KFJ Figure 8 (A-D).

The AM and YM of untreated KFJ were 4.29 and 5.12 log CFU/mL, respectively. In the JF (control) sample, AM exceeded 6.0 log CFU/mL after 8 days (at 4 °C) and >2 days (at 25 °C), while YM crossed the threshold level after 2 days (at 4 °C) and <2 days (at 25 °C) during storage. Under refrigeration, UV-treated juice samples exhibited a shelf life of >18 days in PET and <20 days in glass bottles, while TT extended the shelf life to nearly 24 days in both PET and glass. In comparison, at room temperature, UV-treated juice demonstrated reduced microbial stability, lasting only >6 days in glass bottles. TT juice demonstrated comparatively higher stability, with a shelf life of >8 days in PET and <8 days in glass bottles for AM. The thermal-treated showed higher stability for YM. The KFJ lasts for nearly 20 days (at 4 °C) and up to 8 days (at 25 °C) while stored in glass bottles. In contrast, UV-treated KFJ has lower stability, whereas juice has nearly 16 -and 8-day stability under refrigeration and room temperature storage in b. The findings demonstrated that storage at ambient temperature compromises treatment efficacy, which could be attributed to enhanced proliferation of Yeast under these conditions in contrast to refrigerated storage³³.

The juice samples in glass bottles have lower microbial counts than those in PET bottles, ascribed to GS's excellent oxygen and moisture barrier properties³⁴. The reduced water vapor and transmission rate of glass effectively retards microbial growth by minimizing the external contamination, which is essential for microbial growth. In

addition to that, UV treatment has been shown to extend the shelf-life of fruit juices like starfruit³⁵, watermelon³⁶, orange³⁷, and apple and grape juices³⁸. The effect becomes more pronounced when the juice is stored under refrigerated conditions, suppressing microbial metabolism³⁹. Thus, the combination of glass packaging and UV treatment, along with optimal storage conditions, plays an important role in enhancing the shelf life of KFJ.

3.4.2 Vitamin C

Vitamin C is a main constituent within the nutritional composition of KFJ, which significantly contributes to its antioxidant capacity and scavenges free radicals. Ascorbic acid is highly sensitive to processing and storage conditions¹⁵. Figure 8 (E-F) demonstrates the impact of processing method, packaging, and storage conditions on vitamin C concentration in KFJ. The ascorbic acid (AA) content of control, TT, and UV-treated samples was 34.20, 23.78, and 25.71 mg ascorbic acid/100 mL on the 0th day of storage. The AA content of each treated sample dropped throughout the storage time. The UV-GS-treated sample retained 65.7% of its initial ascorbic acid content on the 24th day of storage, which was higher than that of the TT-treated sample (63.9%) at 4 °C. The effect became more pronounced during storage at room temperature, where the JU-GS sample retained 15.60 units (65.6% retention) on day 24 compared to 16.43 units (63.9% retention) in the TT-treated sample. The Glass bottle exhibited higher vitamin C retention than PET across all treatments. At 25 °C, the JU-GS sample retained 15.60 units compared to 15.30 units in PET, which can be attributed to glass's superior oxygen barrier properties. This effect was more pronounced in fresh juice, where glass bottles showed 12.7% higher retention than PET bottles on the 10th day of storage. Juice stored under refrigerated conditions exhibited greater stability than samples stored at room temperature.

The juice samples stored in glass bottles exhibited higher AA values, which could result from their superior barrier characteristics. This protective effect hindered oxygen permeation and minimized the conversion of ascorbic acid to dehydroascorbic acid. In contrast, juice stored in PET bottles had lower concentrations of vitamin C due to the limited barrier properties of PET against moisture and gases, which allowed oxygen migration into the product, thereby promoting the oxidative degradation of vitamin C^{34,40}.



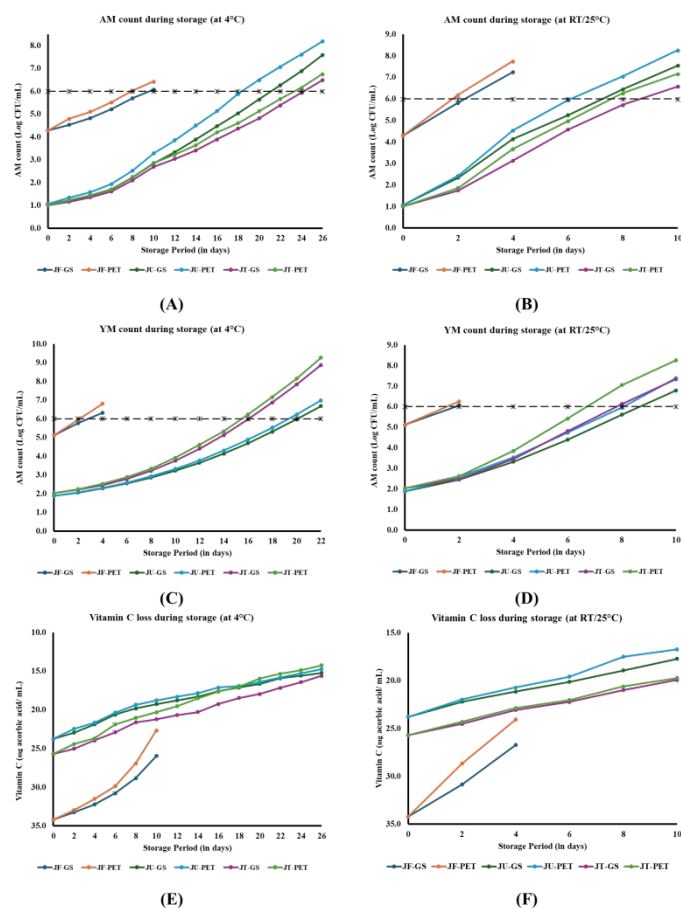


Figure 8: Shelf-life evaluation of control, thermally treated, and UV-treated KFJ stored in glass and PET bottles under refrigerated and room temperature conditions: Aerobic mesophiles count at (A) 4 °C and (B) room temperature, Yeast and mold count at (C) 4 °C and (D) room temperature; and Vitamin C concentration at (E) 4 °C and (F) room temperature.

Conclusions

The study optimized the UV as a non-thermal treatment to lower the vitamin C loss and maximize AM's log reduction. The optimal conditions chosen were 25 minutes of UV exposure at a distance of 5 cm between juice and UV lamp, which resulted in a predicted vitamin C loss of 34.06%, 3.54, and 3.49 log reduction of AM and YM, respectively. Experimental validation showed accuracies of 90.66% for vitamin C loss, 92.37% for YM reduction, and 93.56% for AM reduction. The ANN model (2-15-1 for AM and 2-13-1 for vitamin C loss) has better predictive ability, fitting, and accuracy than RSM. The Weibull distribution model provided a superior fit ($R^2=0.979$) compared to the first-order kinetics model ($R^2=0.983$). The shelf-life study indicated that KFJ stored at 4 °C in glass bottles exhibited enhanced microbial and vitamin C stability compared to room temperature in PET bottles. Notably, the shelf-life of the JU-GS sample improved the shelf-life by nearly six days compared to the untreated sample.

However, some limitations should be acknowledged. Microbial analysis was limited to aerobic mesophiles and yeast and mould counts, and further evaluation of specific foodborne pathogens such as *E. coli*, *Salmonella*, and *L. monocytogenes* would provide a more comprehensive assessment of microbial safety. In addition, shelf-life assessment mainly considered microbial stability and vitamin C retention, while inclusion of other quality attributes such as phenolic compounds, flavonoids, antioxidant activity, and sensory characteristics could provide a broader understanding of the impact of UV treatment on juice quality.

Although the present work was conducted using a laboratory scale batch UV system, the optimized treatment conditions provide a useful basis for the development of pilot scale or continuous flow UV processing systems. Future studies should therefore focus on evaluating additional quality parameters, assessing pathogen inactivation, optimizing reactor design for continuous processing, and examining the industrial feasibility of UV treatment for commercial juice processing.

Author contributions

Vimal Challana: Conceptualization, Methodology, Investigation, Formal analysis, Software, Writing - original draft. **Ankita Naykodi:** Writing -review & editing, Supervision. **Shivanand Shirkole:** Software, Formal analysis, Writing - review & editing. **Akshaya K. Sahoo:** Conceptualization, Methodology, Supervision, Project administration, Validation, Writing - review & editing.

Acknowledgements

The authors acknowledge the support provided by Jeet Pankaj Mehta, Prashant Mahesh Singh, Shubhada Gad, Nikita Sanjay Bhatkar and Keshram Dulait from the Department of Food Engineering and Technology, Institute of Chemical Technology, Mumbai, ICT-IOC Campus, Bhubaneswar, India (751013).

Conflicts of interest

There are no conflicts to declare.

Funding

This research received no specific grant from any funding agency.

Data availability

The datasets used, analyzed, and generated during this study are included in the article and are available from the corresponding author upon reasonable request.

Abbreviation



KFJ: Kinnow fruit juice; **AM:** Aerobic mesophiles; **YM:** Yeast and Molds; **UV:** Ultraviolet; **GS:** Glass; **PET:** Polyethylene terephthalate; **CFU/mL:** Colony-forming units per milliliter; **JU:** UV-treated juice, **JT:** Thermal-treated juice; **TT:** Thermal treatment; **AA:** Ascorbic acid.

References

- Department of Agriculture & Farmers Welfare, *Agricultural Statistics at a Glance 2022* 2023.
- M. K. Mahawar, K. Jalgaonkar, B. Bibwe, B. Bhushan, V. S. Meena and R. K. Sonkar, Post-harvest processing and valorization of Kinnow mandarin (*Citrus reticulata* L.): A review, *Journal of Food Science and Technology*, 2020, **57**, 799-815.
- R. Kumar, Kinnow: Punjab's king of fruit-A review, *Just agriculture*, 2020, **1**, 294-298.
- S. A. Ilame and S. V. Singh, Physico-chemical properties of ultrafiltered kinnow (mandarin) fruit juice, *Journal of Food Science and Technology*, 2018, **55**, 2189-2196.
- S. V. Singh, J. R. K. and A. K. and Gupta, Adsorptive Reduction of Naringin from Kinnow Mandarin Juice with Non-ionic Macroporous Adsorbent Resin, *Indian Chemical Engineer*, 2016, **58**, 136-156.
- S. S. Purewal and K. S. and Sandhu, Nutritional Profile and Health Benefits of Kinnow: An Updated Review, *International Journal of Fruit Science*, 2020, **20**, S1385-S1405.
- A. Bhattacharjee and S. Chakraborty, Design of a batch Ohmic heater and evaluating the influence of different treatment conditions on quality attributes of kinnow (*Citrus nobilis* × *Citrus deliciosa*) juice, *Innovative Food Science & Emerging Technologies*, 2022, **82**, 103186.
- R. Bhardwaj and S. Mukherjee, Effects of fruit juice blending ratios on kinnow juice preservation at ambient storage condition, *African Journal of Food Science*, 2011, **5**, 281-286.
- R. Bhardwaj and U. Nandal, Effect of storage temperature on physico-chemical and sensory evaluation of kinnow mandarin juice blends, *Journal of Food Processing & Technology*, 2014, **5**, 1-4.
- A. Iqbal, N. Muhammad, A. Ammara, A. Kashif, A. N. Muhammad, S. Muhammad, M. Faiqa and A. and Siddeeg, The impact of ozonation on the physicochemical properties, antioxidant potential and shelf life of Kinnow (*Citrus Reticulata* Blanco) juice, *International Journal of Food Properties*, 2022, **25**, 2551-2560. DOI: 10.1039/D5FB00788G
- A. Iqbal, N. Muhammad, A. Ammara, Q. T. Mahmood, K. Waseem, M. Faiqa, R. Salim-Ur, R. Abdul, Z. K. Muhammad, A. Naushad, N. Asad and I. A. and Mohamed Ahmed, Quality evaluation of ozone-processed Kinnow (*Citrus reticulata* Blanco) juice at ambient temperature, *International Journal of Food Properties*, 2023, **26**, 2420-2432.
- V. Yemmireddy, A. Adhikari and J. Moreira, Effect of ultraviolet light treatment on microbiological safety and quality of fresh produce: An overview, *Front Nutr*, 2022, **9**, 871243.
- Y. Kebbi, A. I. Muhammad, A. S. Sant'Ana, L. do Prado-Silva, D. Liu and T. Ding, Recent advances on the application of UV-LED technology for microbial inactivation: Progress and mechanism, *Comprehensive Reviews in Food Science and Food Safety*, 2020, **19**, 3501-3527.
- S. Chakraborty, P. S. Rao and H. N. Mishra, Effect of combined high pressure-temperature treatments on color and nutritional quality attributes of pineapple (*Ananas comosus* L.) puree, *Innovative Food Science & Emerging Technologies*, 2015, **28**, 10-21.
- V. Challana, A. M. Kaimal, S. Shirkole and A. K. Sahoo, Comparative analysis and investigation of ultrasonication on juice yield and bioactive compounds of kinnow fruit using RSM and ANN models, *Scientific Reports*, 2025, **15**, 9859.
- B. S. Kalsi, S. Sandhya, A. M. Shafiq and G. K. and Sidhu, Comparison of ANN and ANFIS modeling for predicting drying kinetics of *Stevia rebaudiana* leaves in a hot-air dryer and characterization of dried powder, *International Journal of Food Properties*, 2023, **26**, 3356-3375.
- R. Zalpouri, M. Singh, P. Kaur, S. Singh, S. Kumar and A. Kaur, Mathematical and artificial neural network modelling for refractance window drying kinetics of coriander (*Coriandrum sativum* L.) followed by the determination of energy consumption, mass transfer parameters and quality, *Biomass Conversion and Biorefinery*, 2025, **15**, 967-983.
- M. A. J. S. van Boekel, On the use of the Weibull model to describe thermal inactivation of microbial vegetative cells, *International Journal of Food Microbiology*, 2002, **74**, 139-159.



19. S. Pipliya, S. Kumar and P. P. Srivastav, Impact of cold plasma and thermal treatment on the storage stability and shelf-life of pineapple juice: A comprehensive postharvest quality assessment, *Food Physics*, 2024, **1**, 100025.
20. Y.-H. Kim, S.-G. Jeong, K.-H. Back, K.-H. Park, M.-S. Chung and D.-H. Kang, Effect of various conditions on inactivation of Escherichia coli O157: H7, Salmonella Typhimurium, and Listeria monocytogenes in fresh-cut lettuce using ultraviolet radiation, *International journal of food microbiology*, 2013, **166**, 349-355.
21. S. Simmons, C. Dale, J. Holt, K. Velasquez and M. Stibich, in *Ultraviolet Light in Human Health, Diseases and Environment*, ed. S. I. Ahmad, Springer International Publishing, Cham, 2017, DOI: 10.1007/978-3-319-56017-5_21, pp. 255-266.
22. H. Nakashima, A. Utsunomiya, J. Takahashi, N. Fujii and T. Okuno, Hazard of ultraviolet radiation emitted in gas metal arc welding of mild steel, *Journal of Occupational Health*, 2016, **58**, 452-459.
23. R. Shamsudin, N. M. Adzahan, Y. P. Yee and A. Mansor, Effect of repetitive ultraviolet irradiation on the physico-chemical properties and microbial stability of pineapple juice, *Innovative Food Science & Emerging Technologies*, 2014, **23**, 114-120.
24. R. Shamsudin, N. Mohd Adzahan, Y. Pui Yee and A. Mansor, Effect of repetitive ultraviolet irradiation on the physico-chemical properties and microbial stability of pineapple juice, *Innovative Food Science & Emerging Technologies*, 2014, **23**, 114-120.
25. A. Torkamani and M. Niakousari, Impact of UV-C light on orange juice quality and shelf life, *International Food Research Journal*, 2011, **18**, 1265.
26. V. R. de Souza, V. Popović, S. Bissonnette, I. Ros, L. Mats, L. Duizer, K. Warriner and T. Koutchma, Quality changes in cold pressed juices after processing by high hydrostatic pressure, ultraviolet-c light and thermal treatment at commercial regimes, *Innovative Food Science & Emerging Technologies*, 2020, **64**, 102398.
27. S. Sablani, L. Opara and K. Al-Balushi, Influence of bruising and storage temperature on vitamin C content of tomato fruit, *Journal of Food Agriculture and Environment*, 2006, **4**, 54.
28. B. Hakguder Taze, S. Unluturk, S. Buzrul and H. Alpas, The impact of UV-C irradiation on spoilage microorganisms and colour of orange juice, *J Food Sci Technol*, 2015, **52**, 1000-1007.
29. R. Zalpour, M. Singh, P. Kaur, A. Kaur, K. K. Gaikwad and A. Singh, Drying Kinetics, Physicochemical and Thermal Analysis of Onion Puree Dried Using a Refractance Window Dryer, *Journal*, 2023, **11**.
30. B. S. Kalsi, S. Singh, M. S. Alam and G. K. Sidhu, Comparison of ANN and ANFIS modeling for predicting drying kinetics of Stevia rebaudiana leaves in a hot-air dryer and characterization of dried powder, *International Journal of Food Properties*, 2023, **26**, 3356-3375.
31. S. Pipliya, S. Kumar and P. P. Srivastav, Modeling of the inactivation kinetics of aerobic mesophiles and yeasts and molds natural microbiota in nonthermal plasma-treated pineapple (*Ananas comosus*) juice, *Journal of Food Science*, 2023, **88**, 3905-3919.
32. A. C. Polydera, N. G. Stoforos and P. S. Taoukis, Comparative shelf life study and vitamin C loss kinetics in pasteurised and high pressure processed reconstituted orange juice, *Journal of Food Engineering*, 2003, **60**, 21-29.
33. S. C. Andrés, L. Giannuzzi and N. E. Zaritzky, The effect of temperature on microbial growth in apple cubes packed in film and preserved by use of orange juice, *International Journal of Food Science and Technology*, 2004, **39**, 927-933.
34. S. B. M. Jaime, R. M. V. Alves and P. F. J. Bócoli, Moisture and oxygen barrier properties of glass, PET and HDPE bottles for pharmaceutical products, *Journal of Drug Delivery Science and Technology*, 2022, **71**, 103330.
35. R. Bhat, S. B. Ameran, H. C. Voon, A. A. Karim and L. M. Tze, Quality attributes of starfruit (*Averrhoa carambola* L.) juice treated with ultraviolet radiation, *Food Chemistry*, 2011, **127**, 641-644.
36. M. Feng, K. Ghafoor, B. Seo, K. Yang and J. Park, Effects of ultraviolet-C treatment in Teflon®-coil on microbial populations and physico-chemical characteristics of watermelon juice, *Innovative Food Science & Emerging Technologies*, 2013, **19**, 133-139.
37. Ç. U. Pala and A. K. Toklucu, Microbial, physicochemical and sensory properties of UV-C processed orange juice and its microbial stability



- during refrigerated storage, *LWT - Food Science and Technology*, 2013, **50**, 426-431.
38. A. Müller, L. Noack, R. Greiner, M. R. Stahl and C. Posten, Effect of UV-C and UV-B treatment on polyphenol oxidase activity and shelf life of apple and grape juices, *Innovative Food Science & Emerging Technologies*, 2014, **26**, 498-504.
39. L. S. Briones, J. E. Reyes, G. E. Tabilo-Munizaga and M. O. Pérez-Won, Microbial shelf-life extension of chilled Coho salmon (*Oncorhynchus kisutch*) and abalone (*Haliotis rufescens*) by high hydrostatic pressure treatment, *Food Control*, 2010, **21**, 1530-1535.
40. A. Jacob, I. P. Sudagar, R. Pandiselvam, P. Rajkumar and M. Rajavel, Effect of packaging materials and storage temperature on the physicochemical and microbial properties of ultrasonicated mature coconut water during storage, *Food Control*, 2023, **149**, 109693.

View Article Online
DOI: 10.1039/D5FB00788G



Data availability

The datasets used, analyzed, and generated during this study are included in the article and are available from the corresponding author upon reasonable request.

