



Effect of ultrasound for postharvest preservation of carrot from an economic and environmental perspective: Experimentation and deterministic optimization

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ABSTRACT

The promising potential of organic agents in elevating food preservation during the minimal processing of fruits and vegetables has surfaced as a notable trajectory. The objective of this work was to evaluate the effectiveness of citric acid and ultrasounds power during carrot sanitization considering various acid concentration and exposition times. To this end, optimization and mathematical modeling tools are employed to assess the implementation of ultrasound technology (US) and citric acid for improved carrot preservation, considering both economic and environmental perspectives. The foregoing is based on an Mixed-Integer Nonlinear Programming (MINLP) optimization problem which allows the selection of which conditions of citric acid concentration and ultrasound time are economically suitable as well as the evaluation of their environmental impact. The model and optimization were generated from experimental data obtained at different sanitization treatments of carrots with citric acid (150, 400, and 900 ppm for 0, 15, 30, 45, 60, 90, and 120 min) in static and Ultrasound baths. Citric acid content, color parameters, and growth of microorganisms in the carrots during storage at 4°C (days 0, 3, 6, and 9) were evaluated. The citric acid and moisture content in carrots increased with the concentration of citric acid in sanitizing solution. Ultrasound increased the citric acid content in carrots by up to 17 %, particularly during the treatment process. However, the optimization results showed that, at 900 ppm of citric acid, both with and without ultrasound technology, similar improvements in shelf life were observed, including lower microbial loads and reduced color changes up to the sixth day of storage. However, the use of US technology increased the cost and environmental impact.

1. Introduction

The use of organic agents to improve food preservation is an alternative for efficient use in the minimal processing of fruits and vegetables (Gabaldón et al., 2007; Piscopo et al., 2019). For the minimally processed vegetables, carrots are among the ten most popular ones, consumed fresh (SIAP, 2023) or processed (juices, nectars, among others) (Hernández-Carranza et al., 2016). In the disinfection and industrial washing of carrots, citric acid is one of the agents used to prevent the growth of microorganisms, reduce browning, and decrease cellular respiration (Kato-Noguchi and Watada, 1997; Rahman et al.,

2011). During the sanitization of the carrot, the citric acid uptake is an important factor to be considered (Miao et al., 2014; Phong et al., 2023). Thus, the study of the mass transfer mechanism of citric acid through the carrot structure is essential to know the amount of citric acid absorbed inside the carrot tissue (Hiranvarachat et al., 2011) and improve the yields of the process (Gómez et al., 2019). The mass transfer mechanism during this process is relatively slow resulting in a significant increase in processing time and costs (Phong et al., 2023). For this reason, it is sought to use technologies that accelerate this process.

In the context of postharvest preservation, a modern and promising alternative lies in the application of ultrasound technology. This method is particularly effective when has been used for sanitization purposes in

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Nomenclature		GAMS	General Algebraic Modeling System
\$	Dollar	kg	Kilograms
c_{H_2O}	Moisture content	LCA	Life Cycle Assessment
c_{citric}	Citric acid concentrations	mg	Milligrams
$\alpha_{b,k}$	Damage produced in category k per unit of chemical product b . One point on	MINLP	Mixed Integer Non-Linear Programming
β_b	Total amount of chemical product b released per unit	MWh	Megawatt hour
δ_d	Standardization factor for damage of category d	OPEX	Operational Expenditure
ω_d	Weighting factor for the damage of category d	ppm	Parts per million
ΔE	Color Difference	P	power
CAPEX	Capital Expenditure	t	Time
CFU	Colony-Forming Unit	t	Ton
g	Grams	US	Ultrasound
		WI	Whiteness Index
		y	year

combination with substances like citric acid. While traditional preservation techniques have been relied upon for ages to control microbial growth and enzymatic activities, ultrasound introduces a contemporary twist. This method can substantially reduce microbial contamination and enzymatic reactions, thereby significantly prolonging the shelf life of the products. Unlike chemical additives, this innovative approach offers a sustainable and efficient solution to enhance postharvest preservation across different types of food items.

Ultrasound technology has garnered considerable attention in recent years due to its non-thermal, non-destructive, and environmentally friendly nature. The synergy between ultrasound and citric acid, a natural compound known for its antimicrobial and antioxidative properties, holds substantial promise compared to traditional methods. This phenomenon can be attributed to the disruption of cell membranes and the alteration of biochemical reactions induced by ultrasound (US), further potentiated by citric acid's intrinsic properties (Siucińska and Kono-packa, 2014; Gallo et al., 2018; Bhargava et al., 2020). These cause a series of effects when they pass through a material, including the formation of microcurrents, the successive compressions and decompressions produced by cavitation (pressure changes) which promote mass transfer (Miano et al., 2016) and thus reduce the processing time (Bhargava et al., 2020). In addition, US improves the quality of food (Alegria et al., 2009; Ding et al., 2015) and reduces the growth of microorganisms (Virto et al., 2005; Sagong et al., 2011; São José and Vanetti, 2012; Bhargava et al., 2020). US has been used to accelerate the mass transfer of organic acids in vegetables (Khaire et al., 2022; São José et al., 2014; Ghafoor et al., 2014), fruits (Zhang et al., 2020) and meat (Goli et al., 2011; Gómez-Salazar et al., 2018). This technique also holds the potential to better preserve the sensory attributes, nutritional quality, and overall freshness of foods, aligning with consumer demand for minimally processed and healthier alternatives. Besides, the reduced reliance on chemical additives aligns with the growing emphasis on sustainable practices and cleaner labels in the food industry.

In addition, when a technology is implemented in a process and scales this to industrial conditions, it is essential to know its environmental impact and the cost of the process (Turton et al., 2012). Also, these aspects must be strictly linked to obtaining high-quality products that preserve the natural characteristics of the product as much as possible (Nikitenko and Chemat, 2015). In the ultrasound application during the sanitization of carrots by immersion in citric acid, two aspects must be considered to evaluate their environmental and economic impact: the citric acid concentration and the conditions of ultrasound. The implementation of ultrasounds in a process can increase operating costs (associated with the cost of materials and the cost of utilities) (Turton et al., 2012). The environmental impact of the process, due to energy consumption, can be evaluated through the Eco-indicator 99 methodology (Sayyaadi, 2020; Gebreslassie et al., 2009), which is used in the Life Cycle Assessment (LCA). This methodology has been widely

used to estimate the environmental impact of a product or a process throughout its life cycle (Silva and Sanjuán, 2019).

Optimization is a valuable tool in food engineering for the efficient operation of processing systems yielding a highly acceptable product. In industrial processes, the quality characteristics of the final products and the design variables of the different equipment to operate in conditions of minimum energy consumption should be described, besides the environmental impact and operating costs (Gómez-Salazar et al., 2022). Such calculations can be carried out with deterministic optimization based on mathematical models. These models enable researchers to capture intricate relationships between variables that influence the effectiveness of organic agents, such as concentration, time, temperature, and the characteristics of the food matrix (Alvarenga et al., 2022). Through mathematical modeling, it becomes feasible to explore a vast range of scenarios, predict outcomes under diverse conditions, and optimize parameters that would be otherwise challenging to manipulate in real-world experiments. In the specific case of investigating the transfer mechanism of citric acid within carrot tissues, mathematical models play a central role in unraveling the diffusion dynamics that govern this process (Alvarenga et al., 2022).

Moreover, mathematical models contribute significantly to the optimization of food preservation strategies. By simulating the behavior of organic agents within the food matrix, these models guide decision-making regarding critical factors and processing conditions. In the case of citric acid transfer in carrots, models assist in identifying the ideal parameters for maximizing citric acid absorption while minimizing waste and preserving product quality. This optimization not only enhances the efficiency of the preservation process but also reduces resource consumption and minimizes the potential for undesirable effects on taste, texture, and nutritional content (Farid, 2010). As advances in computational power and modeling techniques continue to evolve, the application of these models becomes increasingly accessible and relevant. For these reasons, the use of mathematical models in the area of utilizing organic agents for improved food preservation serves as a cornerstone for innovation, enabling researchers and practitioners to devise effective, efficient, and sustainable preservation methods that align with the demands of modern food processing and consumption (Farid, 2010).

Therefore, this work explores the combination of citric acid and ultrasonic technologies as an efficient method to preserve carrots while maintaining their nutritional and sensory properties. A holistic analysis for this system is proposed consisting of two main stages. The first one is an experimental assessment of the use of citric acid and US in carrot preservation. Different output variables such as citric acid concentration, colour, and microbiological properties have been analyzed. The second stage entails a modelling and optimization analysis based on the previous experimental results. This allows for determining the best operating conditions in the carrot treatment to minimize the operating

cost and the environmental burden of the proposed alternative. By integrating these stages, a comprehensive understanding of using citric acid and ultrasonic technology for carrot preservation is achieved.

2. Materials and methods

2.1. Materials

Fresh carrots (Nantes op vitrago) were procured from the local Ira-puato, Guanajuato, Mexico market. Carrots were sorted for uniform size (9 cm), diameter (2.7 cm), and color, ensuring they were free from physical damage. After sorting, the carrots were washed with water to remove any impurities and then cut into cylinders of 2.4 cm diameter and 8.4 cm height. This was done to ensure similar dimensions and regular samples for all treatments. The samples were then randomly divided into three groups. Reagents were provided by Sigma Aldrich (St. Louis, MO, USA); sterilized a distilled water and agars were provided by a local supplier (Proquim, León, Guanajuato, Mexico).

2.2. Experimental conditions with citric acid and Ultrasound

Three different concentrations of citric acid were prepared for the experiments. Granular citric acid monohydrate (Sigma, St. Louis, MO) was mixed with sterilized water to have a final concentration of 150, 400, and 900 ppm in a final volume of 500 mL for each solution. The carrot samples were submerged in each solution for 0, 15, 30, 45, 60, 90, and 120 min in a static bath. Experiments were conducted at cooling temperature (4°C). Samples were taken out of the solutions, rinsed in distilled water for 10 seconds to eliminate the solution remaining on the surface, and blotted with absorbent paper to remove surface water. Then samples were weighed and wrapped in plastic waterproof film and frozen ($-18 \pm 0.5^\circ\text{C}$) until the citric acid and moisture content determinations.

The same procedure was carried out in samples immersed in beakers of 500 mL for each solution of citric acid with ultrasound application. The beakers with the samples were placed in an ultrasonic bath (Branson M2800, Danbury, USA) at 40 kHz and 110 W of output power with 4.5 L of water and sonicated at different intervals (0, 15, 30, 45, 60, 90, and 120 min). The bath temperature was maintained constant at 4°C during the treatment with US application. A water recirculation system was used to keep a constant temperature and water temperature in US was monitored with a thermocouple. A calorimetric method was used to calculate the acoustic power applied to the carrot samples (Gómez-Salazar et al., 2018). For that, the temperature rise was monitored with a thermocouple during the first 180 s of the US treatment. The $\delta T/\delta t$ values were obtained from the graph of temperature as a function of time:

$$P = MC_p \bullet \frac{\delta T}{\delta t} \quad (1)$$

where P is the ultrasonic power (W), M is the mass of the fluid undergoing (kg), C_p is the specific heat of the fluid at constant pressure (J/kgK), and $\delta T/\delta t$ is the increase of temperature (K/s).

In order to study the effect of the treatments on the color and growth of microorganisms during refrigeration, carrots treated with different concentrations of citric acid (150, 400, and 900 ppm) for 15 min without and with US were collected and transferred to sterile plastic bags and stored at 4°C. During storage, sampling was carried out on days 0, 3, 6, and 9. Each experiment was replicated three times, and the means of microbial populations (log CFU/g) and color parameters were calculated.

2.3. Determination of citric acid content

The citric acid concentration was estimated using the pyridine-acetic

anhydride method (Marier and Boulet, 1958). To determine the quantity of citric acid, 30 g of carrot tissue which was previously triturated in Mini-mixer equipment (Ufesa BP4530) and 200 mL of water from a MilliQ plus system (Millipore, Billerica, MA, USA) were placed in a 300 mL volumetric flask. The flask containing the mixture was put into a water bath at 80°C and heated for 45 min. Afterward, the homogenate was diluted with water and filtered (Whatman #1 filter paper) to obtain the carrot extracts. Then, in an ice bath, 1 mL of the sample extract was added to 1.3 mL of pyridine and mixed in a vortex. The solution was mixed with 5.7 mL of acetic anhydride. The test tubes were placed in a water bath at 32 °C for 30 min. The optical density was measured with a spectrophotometer at 420 nm and the citric acid contents of the sample were estimated with reference (same reaction mixture replacing 1.0 mL of sample extract with distilled water) to the standard. At least 4 replications were carried out for each measurement. The method was validated by injecting a known amount of citric acid into small pieces of carrot and comparing those quantities with the values obtained following the extraction and determination procedure described above. The method was successfully validated ($R^2 = 0.99$).

2.4. Determination of moisture content

The moisture content of each carrot sample over time was determined by drying the sample until constant weight at $103 \pm 2^\circ\text{C}$ (AOAC, 1997).

2.5. Color analysis

Color parameters were measured in the carrot samples before and after processing. A Color Gard System colorimeter (Color Flez, Hunter Lab, Reston VA) was used in the reflection mode. Lightness to darkness (L^*), redness to greenness (a^*), and yellowness to blueness (b^*) were quantified in all of the carrots in at least four different points of the product. The instrument was calibrated using the black tile and the white tile standards. The net color difference (ΔE^*) was determined using L^* , a^* , and b^* values according to Tiwari et al. (2021), comparing them with the values of unprocessed samples:

$$\Delta E^* = \sqrt{(L^* - L_0)^2 + (b^* - b_0)^2 + (a^* - a_0)^2} \quad (2)$$

Whiteness index score (WI) was determined according to Piscopo et al. (2019), following the equation:

$$WI = 100 - [(100 - L^*)^2 + a^{*2} + b^{*2}]^{0.5} \quad (3)$$

2.6. Microbiological analyses

Mesophilic aerobic counts were determined with nutritive agar, surface inoculation and 24 h incubation according to Mexican regulation (NOM-092-SSA1-1994). Mold and yeast counts were performed using potato dextrose agar at pH 3.5 (adjusted with 10 % formic acid), surface inoculation and 5 days incubation according to Mexican regulation (NOM-111-SSA1-1994).

2.7. Modelling and Optimization

Once the experiments were completed, and to scale up the carrot treatment at the industrial level, mathematical modeling and optimization tools were used to evaluate the implementation of US technology as well as to learn how to use citric acid as a preservative to best preserve the carrot from an economic and environmental perspective. The modeling was performed assuming a carrot treatment plant capable of processing 20 t/h, meeting a production value demand of 170 thousand t/year, and guaranteeing more than half of the total annual production in Mexico, which exceeded 331 thousand t, with Guanajuato being the main producer, followed by Puebla and Zacatecas (SIAP, 2023).

Fig. 1 shows a diagram with a general outline of the methodology proposed in this work to assess carrot production with novelty preservation techniques. Each of the stages was aimed at scaling up the results of the experiments and providing an optimal result of the conditions to obtain better economics, reduce the environmental impact, and comply with biological and sensory requirements for carrot consumption.

In order to model the process correctly, firstly, it was necessary to collect experimental data. The previous sections showed how these experimental data were obtained. After the information was collected, experimental correlations were developed. These mathematical models were essential in this work to optimize, from a deterministic approach, the proposed problem. Besides, these equations could predict the behavior of the system, avoiding the execution of new experiments. In this study, polynomial regression models were employed to develop the necessary experimental correlations. The input variable for these models was immersion time (t), used to calculate the concentrations of water (c_{H_2O}) and citric acid (c_{citric}) in the carrot samples.

The resulting correlations based on experimental results were shown in Eqs. 4 through 15. Each of the Eqs. (4 to 9) described the kinetic data obtained at different citric acid concentrations (c_{citric}), namely, 150 ppm (Eqs. 4–5), 400 ppm (Eqs. 6–7), and 900 ppm (Eqs. 8–9), representing the immersion with (Eqs. 4, 6, 8) and without (Eqs. 5, 7, 9) the use of US technology as a function of the immersion time (t). Eqs. 10 to 15 displayed the models of moisture content after the carrot treatment

(c_{H_2O}) at different concentrations, i.e., 150 ppm (Eqs. 10–11), 400 ppm (Eqs. 12–13), and 900 ppm (Eqs. 14–15), with (Eqs. 10, 12, 14) and without (Eqs. 11, 13, 15) US technology. It is important to note that these correlations were validated against experimental data.

$$c_{citric} = (4.356 \times 10^{-10}) \times t^2 + (6.655 \times 10^{-6}) \times t + 1.118 \times 10^{-1} R^2 = 0.995 \quad (4)$$

$$c_{citric} = - (9.640 \times 10^{-18}) \times t^4 - (6.232 \times 10^{-14}) \times t^3 + (1.903 \times 10^{-9}) \times t^2 - (3.521 \times 10^{-6}) \times t + 1.148 \times 10^{-1} R^2 = 0.988 \quad (5)$$

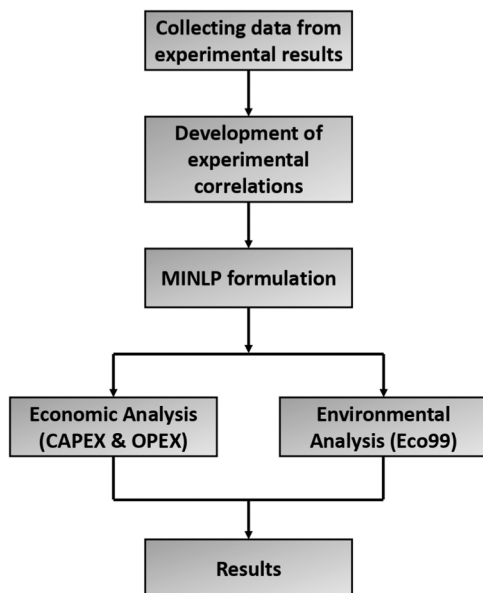


Fig. 1. General methodology for modeling and optimization.

$$c_{citric} = - (2.383 \times 10^{-13}) \times t^3 + (2.077 \times 10^{-9}) \times t^2 + (1.342 \times 10^{-5}) \times t + 1.116 \times 10^{-1} R^2 = 0.990 \quad (6)$$

$$c_{citric} = - (5.492 \times 10^{-13}) \times t^3 + (5.845 \times 10^{-9}) \times t^2 + (5.311 \times 10^{-6}) \times t + 1.142 \times 10^{-1} R^2 = 0.998 \quad (7)$$

$$c_{citric} = - (5.3 \times 10^{-19}) \times t^5 + (1.022 \times 10^{-14}) \times t^4 - (6.987 \times 10^{-11}) \times t^3 + (1.854 \times 10^{-7}) \times t^2 - (7.425 \times 10^{-5}) \times t + 1.135 \times 10^{-1} R^2 = 0.999 \quad (8)$$

$$c_{citric} = (1.260 \times 10^{-15}) \times t^4 - (1.974 \times 10^{-11}) \times t^3 + (8.914 \times 10^{-8}) \times t^2 - (4.050 \times 10^{-5}) \times t + 1.141 \times 10^{-1} R^2 = 0.991 \quad (9)$$

$$c_{H_2O} = - (1.158 \times 10^{-17}) \times t^4 + (2.209 \times 10^{-13}) \times t^3 - (1.596 \times 10^{-9}) \times t^2 + (5.751 \times 10^{-6}) \times t + 8.690 \times 10^{-1} R^2 = 0.986 \quad (10)$$

$$c_{H_2O} = (4.060 \times 10^{-18}) \times t^4 - (3.235 \times 10^{-15}) \times t^3 - (7.394 \times 10^{-10}) \times t^2 + (6.405 \times 10^{-6}) \times t + 8.689 \times 10^{-1} R^2 = 0.998 \quad (11)$$

$$c_{H_2O} = - (2.435 \times 10^{-17}) \times t^4 + (4.833 \times 10^{-13}) \times t^3 - (3.623 \times 10^{-9}) \times t^2 + (1.289 \times 10^{-5}) \times t + 8.687 \times 10^{-1} R^2 = 0.999 \quad (12)$$

$$c_{H_2O} = - (2.511 \times 10^{-17}) \times t^4 + (5.099 \times 10^{-13}) \times t^3 - (3.943 \times 10^{-9}) \times t^2 + (1.423 \times 10^{-5}) \times t + 8.689 \times 10^{-1} R^2 = 0.999 \quad (13)$$

$$c_{H_2O} = (1.0 \times 10^{-20}) \times t^5 - (2.412 \times 10^{-16}) \times t^4 + (2.418 \times 10^{-12}) \times t^3 - (1.101 \times 10^{-8}) \times t^2 + (2.361 \times 10^{-5}) \times t + 8.688 \times 10^{-1} R^2 = 0.999 \quad (14)$$

$$c_{H_2O} = - (5.617 \times 10^{-17}) \times t^4 + (9.800 \times 10^{-13}) \times t^3 - (6.465 \times 10^{-9}) \times t^2 + (1.927 \times 10^{-5}) \times t + 8.687 \times 10^{-1} R^2 = 0.999 \quad (15)$$

The citric acid concentration was expressed in mg/mg•dm and the moisture content in g water/g sample. The immersion time in citric acid solutions was computed in seconds with a maximum limit of 120 min.

Similarly, sensory limitations were imposed on the maximum acceptable values of ΔE , the Whiteness Index (WI), and the results of microbiological analyses (including fungal, yeast, and mesophile growth) to ensure proper commercialization standards for both

appearance and safety. The value of ΔE had to be less than 5 for color change in the food to be imperceptible. Different grades were set: excellent was between 0 and 1, good was between 1 and 2, normal was between 2 and 4, sufficient was between 4 and 5, and a perceptible change was anything greater than 5. In the case of WI, 100 was the maximum whiteness, and 0 was the minimum whiteness. Finally, for a product with commercial viability, the maximum microbial load was around 10^7 CFU/g (7.0 Log_{10} CFU/g) (Concurso et al., 2020).

Once experimental models were generated and taking into account the restrictions, a Mixed Integer Nonlinear Programming (MINLP) optimization problem was generated and solved in the General Algebraic Modeling System (GAMS) software version 36.2.0 provided by GAMS Software GmbH (for Europe). The model was solved to optimize and select which conditions of citric acid concentration and technology were economically suitable as well as to evaluate their environmental impact. Thus, the main decision variables were the citric acid concentrations for carrot immersion (150, 400, and 900 ppm), the immersion time, and the technology used (US technology or not). For the present work, the model was optimized under the objective function represented in Eq. 16.

$$\min(\text{CAPEX}, \text{OPEX}) = f(c_{\text{citric}}, c_{\text{H}_2\text{O}}, t) \quad (16)$$

OPEX was the operating expenditure of the carrot treatment facility. This item included, mainly, the cost of the raw materials (mainly citric acid), the cost of the utilities (mostly power), and the capital cost associated with the investment or capital expenditure (CAPEX) of the plant. Capital Expenditure (CAPEX) referred to capital expenditures or investments made by a company when acquiring an asset. The CAPEX cost was included in the calculation of the OPEX assuming a 10-year period to recover the initial investment. The equations describing CAPEX and OPEX were described in Eqs. 17 and 18, respectively.

$$\text{CAPEX} = \text{Cost of immersion tank or Cost of immersion tank with US} \quad (17)$$

$$\text{OPEX} = \text{Raw material cost} + \text{Cost of utilities} + \text{annualized CAPEX} \quad (18)$$

The costs for these technologies were calculated using actual data and scaled to a processing capacity of 20 t/h. For the tank, a detailed economic evaluation was carried out based on the procedure of Turton et al. (2012). For the tank with US technology, the cost was estimated based on real equipment and scaled to the proposed production (Bestultrasonic, 2023).

The amount of raw material was equal to the amount of citric acid used, which was the citric acid absorbed in carrots for their preservation. The current cost of citric acid was set to \$4/kg (Wang et al., 2020). The cost of utilities included the cost of energy associated with the process, with a cost of electricity set at \$100/MWh. The economic optimization problem was implemented and solved in GAMS using DICOPT as the solver.

Once the economic optimization was completed, an environmental impact assessment was carried out using the Eco-indicator99 metric. The Eco-indicator99 methodology contemplated three main categories of impact: human health, ecosystem quality, and resource depletion. The Eco-indicator99 was described in Eq. 19.

$$\text{Eco-indicator99} = \sum_b \sum_d \sum_{k \in K} \delta_d \omega_d \beta_b \alpha_{b,k} \quad (19)$$

Where δ_d was the standardization factor for damage of category d , ω_d was the weighting factor for the damage of category d , β_b corresponded to the total amount of chemical product b released per unit of reference flow due to direct emissions, and $\alpha_{b,k}$ represented the damage produced in category k per unit of chemical product b released to the environment. One point on the Eco-indicator99 scale meant one-thousandth part of the annual environmental load of an average European citizen (Gebreslassie et al., 2009).

2.8. Statistics analysis

ANOVAs were performed to determine the treatment's effect on physicochemical and microbiological characteristics. If differences were found, a Tukey test with a significance level of 95 % was applied. The analyses were carried out using the software Stat-graphics plus 5.1 software (Statpoint Technologies Inc., Warrenton, VA, USA).

3. Results and discussion

3.1. Citric acid and moisture content

The experimental results for the acid citric content of the carrot samples are shown in Fig. 2. During the first 15 min of treatment with citric acid and US, no differences on citric acid content in carrots was observed. Subsequently, the citric acid content in carrots increased with treatment time and with the concentration of citric acid in the immersion solution ($p < 0.05$). The higher the concentration of citric acid in the immersion solution, the higher the acid content in the carrot tissue.

A faster increase in the citric content of the samples was observed at 900 ppm of citric acid in immersion solution, whereas this increase was slower in the samples immersed in citric acid at lower concentrations. There are two factors behind this rapid movement of the citric acid on the carrot surface: first, the concentration gradient between the carrot surface and the citric acid solution at the beginning of the immersion process and, second, the high moisture content of the samples (Fig. 2), which easily facilitates citric acid diffusion in carrot tissue (Ramirez et al., 2017). Other authors reported that citric intake and water gain occurred simultaneously during immersion and these two events mutually affected each other (Akköse and Aktaş, 2014). Equilibrium was reached in the samples treated at 900 ppm, after 60 min of immersion in citric acid, with a value of 0.38 mg of citric acid/mg d.m.

The difference in citric acid content in the carrots was evidenced at the end of the treatments. After 120 min of treatment, the citric acid content for samples immersed at 900 ppm of citric acid was close to 0.39 mg of citric acid/mg d.m. In comparison, the citric acid content after 120 min in samples immersed at 400 and 150 ppm of citric acid was 0.22 and 0.17 mg of citric acid/mg d.m., respectively, which is more than two times lower. After the first 15 min of immersion at 900 ppm, there was a large gradient of concentration between the carrot and the citric acid solution, causing a fast penetration of citric acid in carrots, while for the other samples treated at 400 and 150 ppm it occurred at slower rates.

Regarding the US, from the first 60 min an effect of this technology on the citric acid content in carrots was observed. The US increased the citric acid content in the carrot with values of 0.15, 0.17 and 0.43 mg of citric acid/mg d.m., for immersion treatments at 150, 400 and 900 ppm, while for the same immersion time in the treatments without US, the values were 0.14, 0.16 and 0.38 mg of citric acid/mg d.m. At the end of the immersion treatment (120 min), the US increased the citric acid content in carrots by 5, 10 and 17 %, during immersion in solutions at 150, 400 and 900 ppm of citric acid, respectively. These results are due to the acoustic cavitation produced by ultrasound (Miano et al., 2016), which could cause cell disruption and/or matrix rupture inside the carrots, generating microscopic channels that reduce the internal resistance to the mass flow promoting the transfer of citric acid to the carrots.

The initial moisture content of the carrots was 0.878 g/g sample. The moisture content of carrot is an important factor to take into account, because citric acid, due to its high solubility, is mobilized into the carrot tissue in the aqueous phase (Phong et al., 2023).

The average moisture content of the carrot samples during the immersion process at different citric acid concentrations is shown in Fig. 3. It can be observed that the moisture content increased when the immersion time lengthened ($p < 0.05$) and the citric acid concentration rose. This increase was greater in the samples treated with 900 ppm of citric acid compared to the treatments at 400 and 150 ppm.

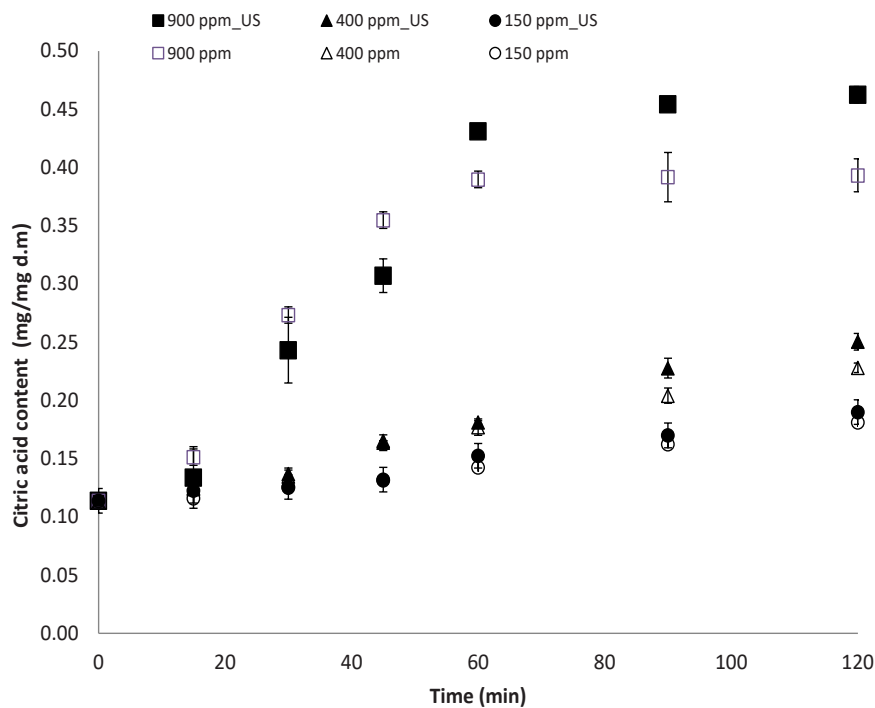


Fig. 2. Kinetics of citric acid content in carrot samples during citric acid treatments.

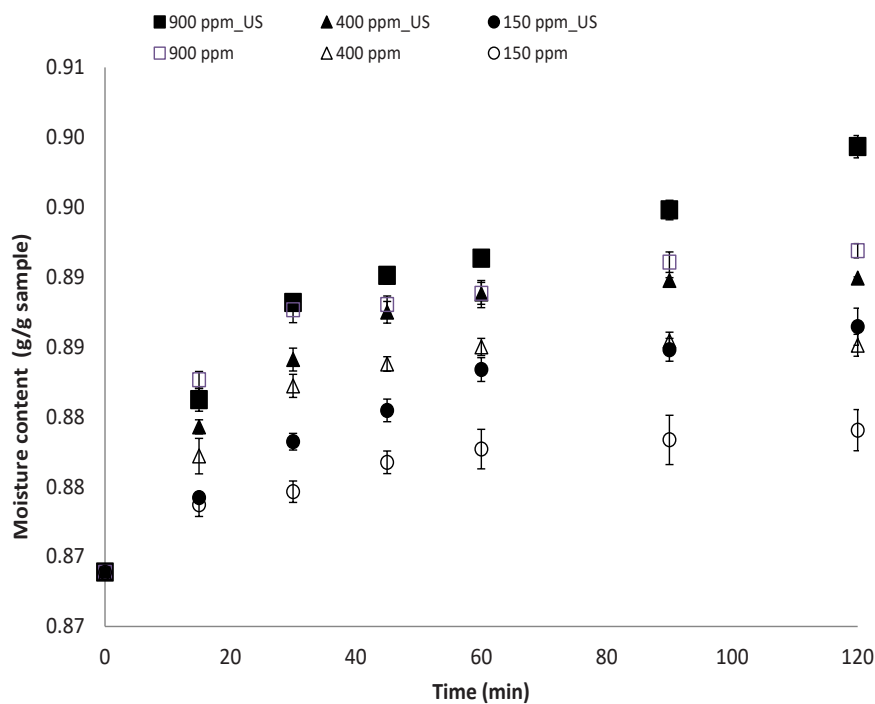


Fig. 3. Kinetics of water content in carrot samples during citric acid treatments.

Regarding ultrasound, the results indicated similar trends to those observed with treatments without ultrasound. Specifically, the moisture content of the carrots increased with both the treatment time and the application of ultrasound ($p < 0.05$). Ultrasound increased the transfer of water from the immersion solution to the carrot, with gains in water moisture content between 0.5 % and 1 % compared to treatments without ultrasonication. This moisture gain was more pronounced in samples treated with ultrasound at a concentration of 900 ppm of citric acid, compared to those treated with ultrasound at 400 and 150 ppm.

These findings can be attributed to ultrasound's ability to enhance the processes of mass transfer (Miano et al., 2016). Although the increases in water content were minimal, this suggests that the carrot samples do not lose moisture during the immersion process in citric acid. This retention of water is crucial because it allows citric acid to penetrate the carrot and enhances the diffusion processes (Ramirez et al., 2017).

3.2. Color analysis

Treatments with citric acid affected the color parameters (Table 1). Compared to the control, the parameter L^* decreased when 150 ppm of citric acid was used in the immersion solution, while at concentrations of 400 and 900 ppm, it increased. The parameters a^* and b^* increased with citric acid concentration compared to the control ($p < 0.05$).

The use of ultrasound in the treatments with citric acid on carrot promoted to a significant change in color parameters ($p < 0.05$). Regarding the beginning of storage (day 0), citric acid treatments at 150 ppm with ultrasound resulted in a darkening of the carrot color in comparison with the raw carrot (control), while the treatments at 400 and 900 ppm with ultrasound increased the luminosity of the carrots. Ultrasound treatment resulted also in alteration of a^* and b^* parameter, which corresponds to yellow and red color, respectively (Table 1). The samples treated with ultrasound and citric acid at 900 ppm showed a greater increase in the red hue.

The storage time affected the color parameters. The L^* values remained constant in control during refrigeration storage, however in samples treated at 150 ppm the values increased while at higher concentration of citric acid, 400 and 900 ppm, the L^* values slowly decreased during storage. Therefore, the use of lower concentrations of citric acid in the immersion solution promotes lightening of carrots in storage, while high concentrations of citric acid in the immersion solution a rapid loss of light is avoided.

Analyzing the total color difference ΔE value, it can be concluded that the treatment caused significant changes in carrots (Table 1). The ΔE value in carrot described the changes in regard to color of control. According to Tiwari et al. (2021), the total color difference value higher than 5 conforms to visible difference. It can be observed that, for the first day of storage, most of the samples treated with different concentrations of citric acid and ultrasound had a value higher than 5 of ΔE and it was in the range from 5.04 to 12.32. Moreover, samples treated at 150 ppm (without and with ultrasound) were characterized by the high value of color difference ΔE , which means that this treatment had a huge impact on the sample's color. These results are related to the values of the

whiteness index (WI), where the WI value decreased in carrots treated with 150 ppm citric acid compared to the control at the beginning of the storage, while for the carrots treated with 400 and 900 ppm, it remained constant. Additionally, the WI value was lower in the 150 ppm with US treatment compared to the other treatments.

3.3. Microbiological analysis

The growth of fungi and molds in carrots without the suggested treatment increased their microbiological load from 3.65 to 8.56 Log_{10} CFU/g during the refrigeration storage (Fig. 4). Immersion citric acid treatments show a significative effect against fungi and molds growth into carrots. In fact, at higher citric acid concentration (900 ppm) and lower storage times (3 days), the best results were obtained. Specifically, the lowest microbiological loads were 3.45 and 3.53 Log_{10} CFU/g for the immersion treatment at 900 ppm with and without US, respectively. Meanwhile, after 6th day of refrigeration storage, there's not significative effect between immersion citric acid treatment and the US technology employed. However, both treatments applied were able to reduce a 25 % the microbiological load for fungi and molds during the 6th and 9th day of refrigeration storage.

In order to measure the growth mesophile in carrots minimally processed carrots during 9 days at refrigeration storage, Mexican standard methods were applied. The native microbiological load was 5.38 Log_{10} CFU/g at the beginning of experiment and this value increased until 9.96 Log_{10} CFU/g at the end of refrigeration storage (Fig. 5). In the same way as fungi and molds growth, immersion citric acid treatments with and without US technology were able to stop growing of mesophiles during the three days of refrigeration storage. The lowest mesophiles microbiological load was 4.95 and 5.06 Log_{10} CFU/g for immersion citric acid treatment of 900 ppm with and without US technology, respectively.

After three days of refrigeration storage in minimally processed carrots, the mesophile microbiological load increased in a significant way. At this level, the immersion citric acid treatment at 900 ppm with and without US technology were the most effective treatments in

Table 1
Color parameters of carrot samples during citric acid treatments.

Treatment	day	L^*	a^*	b^*	ΔE	WI
Control	0	49.86 ± 1.02^a	33.59 ± 0.32^a	40.05 ± 1.11^a		27.57 ± 1.14^a
	3	49.71 ± 1.25^a	32.27 ± 0.93^a	39.86 ± 1.02^a	1.35 ± 0.32^a	28.17 ± 1.45^a
	6	49.23 ± 1.01^a	32.84 ± 1.12^a	40.03 ± 0.82^a	0.98 ± 0.42^a	27.48 ± 1.17^a
	9	49.22 ± 1.12^a	32.84 ± 1.21^a	40.00 ± 0.75^a	0.99 ± 0.46^a	27.50 ± 1.64^a
150 ppm	0	38.16 ± 3.45^b	35.96 ± 0.31^b	43.10 ± 1.52^b	12.32 ± 4.32^b	16.48 ± 3.72^b
	3	46.81 ± 2.31^a	32.30 ± 1.32^a	41.52 ± 1.13^{ab}	3.62 ± 0.42^c	25.19 ± 1.81^a
	6	47.92 ± 1.92^a	31.22 ± 1.15^a	39.08 ± 1.65^a	3.21 ± 0.76^c	27.79 ± 1.63^a
	9	47.75 ± 1.75^a	31.38 ± 1.02^a	39.38 ± 1.47^a	3.12 ± 0.47^c	27.44 ± 1.74^a
400 ppm	0	53.82 ± 0.52^c	34.83 ± 0.52^b	44.50 ± 2.12^{bc}	5.97 ± 2.52^c	27.40 ± 1.15^a
	3	50.69 ± 1.25^a	33.01 ± 0.72^a	41.25 ± 1.15^{ab}	1.57 ± 0.92^a	27.73 ± 1.32^a
	6	50.19 ± 1.08^a	34.83 ± 0.55^b	41.82 ± 1.22^{ab}	2.19 ± 0.86^a	26.22 ± 1.65^a
	9	49.07 ± 1.38^a	35.34 ± 0.86^b	42.35 ± 1.78^{ab}	2.99 ± 0.81^a	24.93 ± 1.09^c
900 ppm	0	52.95 ± 0.41^c	37.96 ± 2.15^b	46.60 ± 2.41^c	7.12 ± 2.81^c	26.99 ± 1.71^a
	3	51.78 ± 1.45^{ac}	35.65 ± 0.92^b	42.40 ± 1.12^{ab}	3.67 ± 1.74^c	26.55 ± 1.26^a
	6	50.87 ± 0.48^a	34.51 ± 1.25^{ab}	42.06 ± 1.41^a	2.43 ± 1.02^a	26.69 ± 1.12^a
	9	50.77 ± 0.54^a	36.53 ± 1.32^b	43.85 ± 0.32^{bc}	4.66 ± 1.65^c	24.80 ± 1.04^c
150 ppm+US	0	32.89 ± 4.21^b	33.62 ± 1.12^a	42.55 ± 1.74^{ab}	7.15 ± 2.15^c	13.72 ± 3.89^b
	3	49.90 ± 1.95^a	32.77 ± 1.21^a	41.62 ± 1.32^{ab}	1.77 ± 0.21^a	27.09 ± 1.62^a
	6	50.70 ± 1.32^a	33.75 ± 1.45^a	42.92 ± 1.25^{ab}	3.10 ± 0.58^c	26.44 ± 1.74^a
	9	51.67 ± 1.52^{ac}	29.95 ± 2.32^a	40.01 ± 1.82^a	4.07 ± 1.42^c	30.48 ± 1.02^d
400 ppm+US	0	50.61 ± 0.32^a	33.34 ± 1.32^a	44.67 ± 1.63^{bc}	4.69 ± 1.28^c	25.53 ± 2.16^{ac}
	3	53.55 ± 0.58^c	34.04 ± 1.28^{ab}	43.97 ± 1.24^{bc}	5.41 ± 1.71^c	27.54 ± 1.78^a
	6	53.61 ± 0.32^c	36.18 ± 1.13^b	36.21 ± 2.92^a	5.96 ± 1.42^c	30.92 ± 1.05^d
	9	51.71 ± 1.90^{ac}	33.71 ± 1.42^a	42.36 ± 1.15^{bc}	2.97 ± 0.54^a	27.46 ± 1.87^a
900 ppm+US	0	51.21 ± 0.45^{ac}	35.67 ± 1.08^b	44.89 ± 2.32^{bc}	5.44 ± 1.41^c	24.71 ± 2.32^a
	3	50.61 ± 0.82^a	33.34 ± 1.05^a	44.67 ± 2.25^{bc}	4.69 ± 1.35^c	25.53 ± 1.95^{ac}
	6	49.01 ± 1.32^a	30.05 ± 1.33^a	39.16 ± 1.42^a	3.75 ± 0.78^c	29.04 ± 1.12^{ad}
	9	48.26 ± 1.75^a	29.10 ± 2.03^a	38.43 ± 1.23^a	5.04 ± 1.32^c	29.29 ± 1.15^{ad}

Values in the same column having different letters were significantly different at $p < 0.05$.

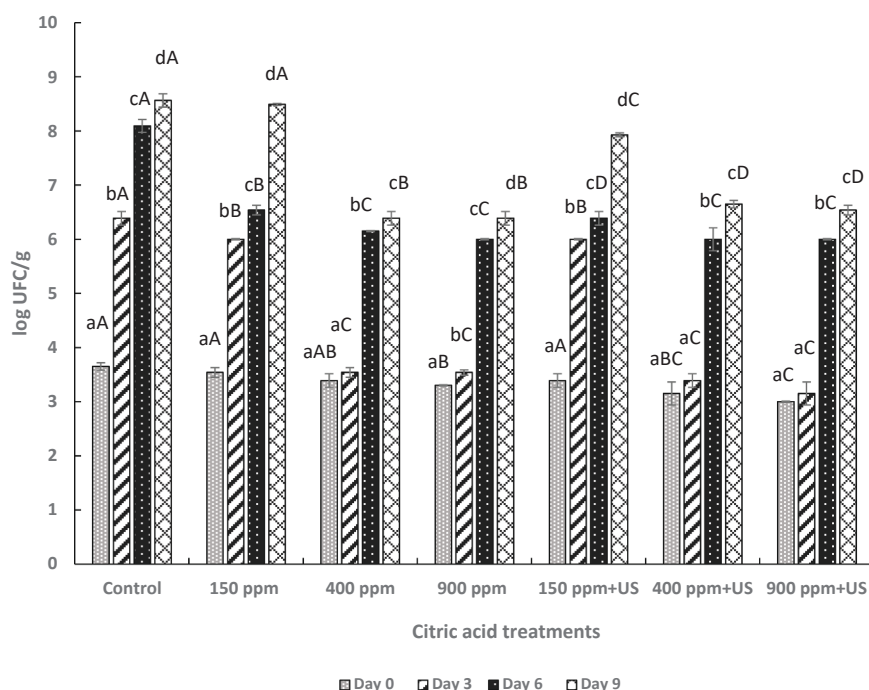


Fig. 4. Growth of Fungi and yeasts in minimally processed carrot during 9 d of storage at 4 °C. Different lowercase letters represent significant differences between days of storage for the same treatment. Different capital letters represent significant differences between treatments for the same day of storage.

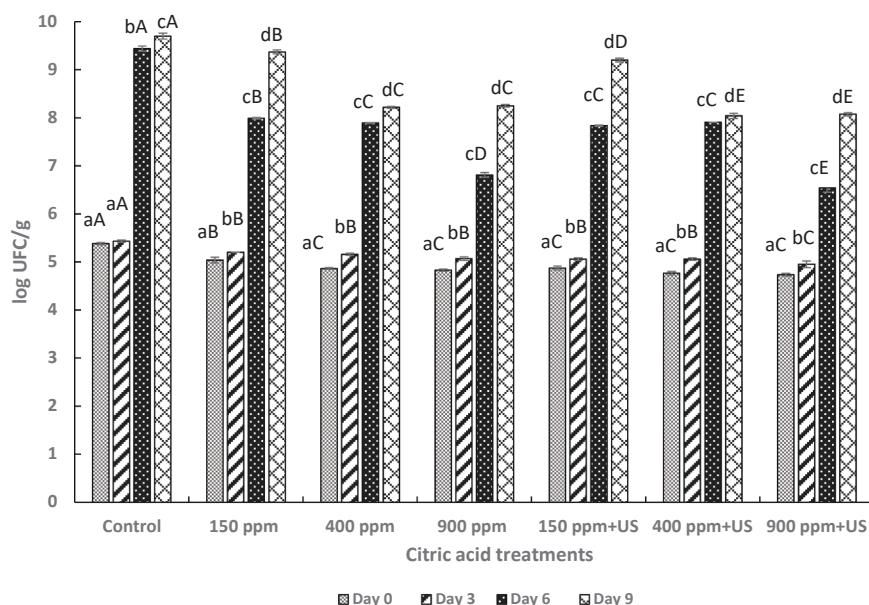


Fig. 5. Growth of Mesophiles in minimally processed carrot during 9 d of storage at 4 °C. Different lowercase letters represent significant differences between days of storage for the same treatment. Different capital letters represent significant differences between treatments for the same day of storage.

stopping mesophile growing into analyzed samples. This postharvest treatment was able to reduce the mesophile microbiological load near to 17 and 15 % respect to control during the 6th and 9th days of refrigeration storage in minimally processed carrots. Finally, immersion citric acid treatment at 150 ppm was not significant in the reduction of microbiological loads in refrigeration storage of carrot with and without employed of US technology.

3.4. Modelling and optimization

This section shows the results of the modeling and deterministic

optimization of the carrot treatment problem. Fig. 6 shows CAPEX on the left axis, and OPEX on the right axis for the different cases assessed in this work. The number of carrots treated is 20 t/h. It is clear that the immersion processes that use US technology are more expensive in terms of CAPEX than those that do not use US technology. With the immersion of carrots using US technology in citric acid solutions at 150, 400, and 900 ppm, CAPEX of 5190 [\$/ (t/h)] is obtained, specifying that the unit is equal for all the cases since the processing capacity is the same. Without the use of US technology, CAPEX at 150, 400, and 900 ppm is 4600 [\$/ (t/h)]. In this technology, both the tank and the ultra-sound system are equal for all the citric acid concentrations. The

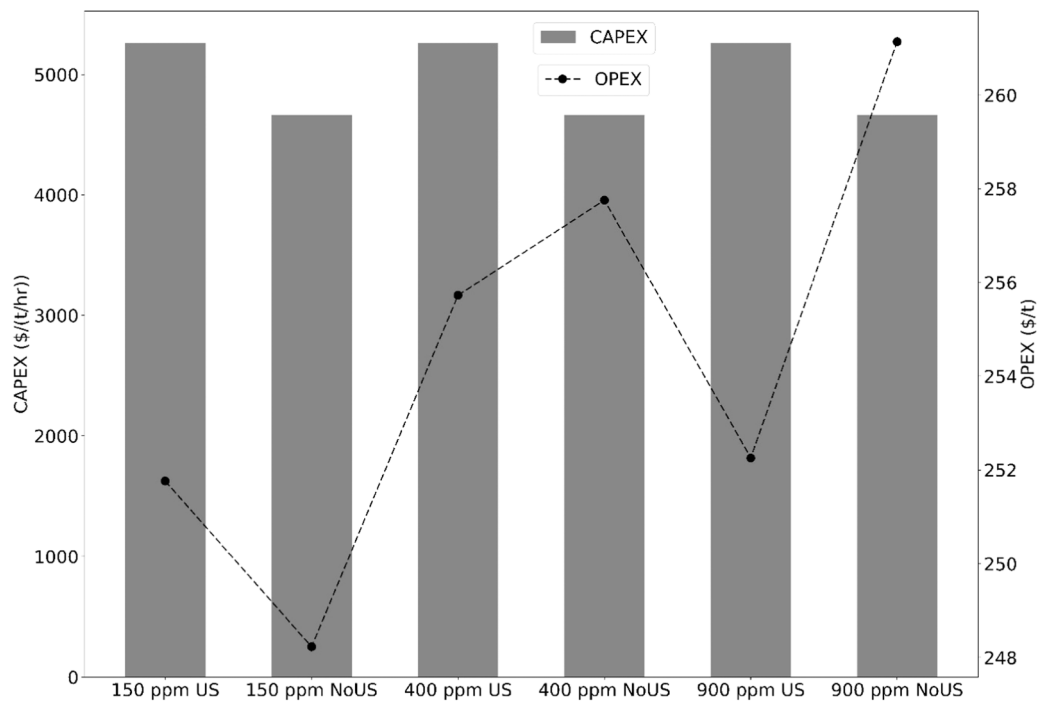


Fig. 6. Economic results of the carrot minimal process.

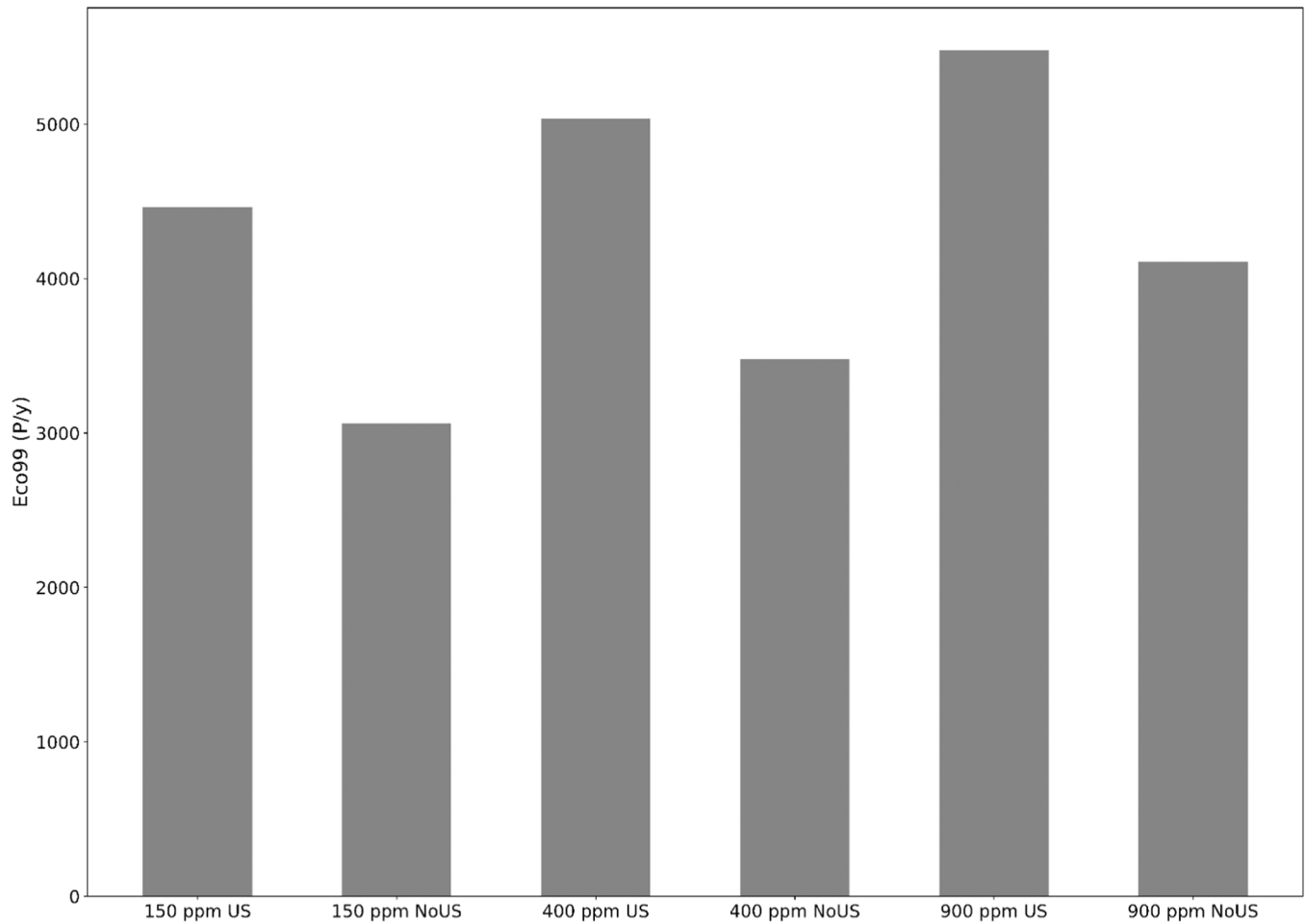


Fig. 7. Results of the environmental impact of the carrot minimal process.

use of CAPEX with US technology is 11.5 % higher versus the system without it.

OPEX for each of the citric acid concentrations changes significantly. In this case, the use of different amounts of citric acid and the introduction of power for US technology has a substantial impact on operating expenses. The amount of citric acid consumed for each of the situations depends on two variables, the desired concentration of citric acid and the kinetic of the citric acid absorption into the carrot. The first one is a parameter of the proposed problem and different cases have been analyzed. The absorption of citric acid in the carrot is computed based on the experimental correlation developed using the experimental results. The concentration of 150 ppm citric acid without US technology shows the lowest OPEX, around 248 [\$/ton], as opposed to the same concentration with the use of US technology with an OPEX of 251 [\$/ton]. As the concentration of citric acid rises and because of the large number of carrots immersed, OPEX rises considerably, resulting in the concentration of 400 ppm with and without US technology, values of 255 and 258 [\$/ton], respectively. In this particular case, it is evident that a higher amount of citric acid is required without the use of US technology, which raises OPEX. For the 900 ppm concentration, OPEX with US technology is close to 252 [\$/ton], while the highest OPEX value is evident at 900 ppm without the use of US technology, with a value close to 262 [\$/ton]. This is about a 5.5 % difference in operating costs per ton of carrots processed using lower concentrations of citric acid (150 ppm) compared to higher concentrations of citric acid (900 ppm). This may seem like a small difference, but considering the large number of carrots processed per hour (20 t/h), the number is

significant. So up to this point, it is convenient to use a small concentration of citric acid to reduce the cost associated with the treatment. In addition, the introduction of US technology clearly raises the CAPEX and OPEX of carrot processing. However, to determine the benefits in the preservation of carrots by introducing more citric acid or the US technology; environmental aspects, the evaluation of biological and sensory aspects of carrots, such as fungal growth, yeast, mesophilic, ΔE , and WI must also be considered.

The generated environmental impact is a central aspect to be considered in the selection of carrot processing technology. Fig. 7 shows the environmental impact using Eco-indicator99 to evaluate the different concentrations proposed, with and without the effect of US technology. The results of the Eco-indicator99 evaluation initially reveal that the use of US technology has a notable environmental impact versus its counterpart, i.e., the use of power to carry out the US technology increases between 25 % and 30 % of the P/y for each concentration.

The objective of this work is to minimize the environmental impact thus reducing the Eco-indicator99 assessment score, especially the process with the 150 ppm concentration, and the one that does not make use of US technology has the lowest environmental impact with 3061 [P/y], followed by the 400 ppm without US technology with 3479 [P/y], and with 4109 [P/y] the 900 ppm without US technology. The highest environmental impact is presented with the use of 900 ppm with the use of US technology with a value of 5479 [P/y]. If environmental impact is considered independently, the use of 150 ppm can be an option without the use of US technology, which relates to the economic factor. However, the sensory and biological effects of using different

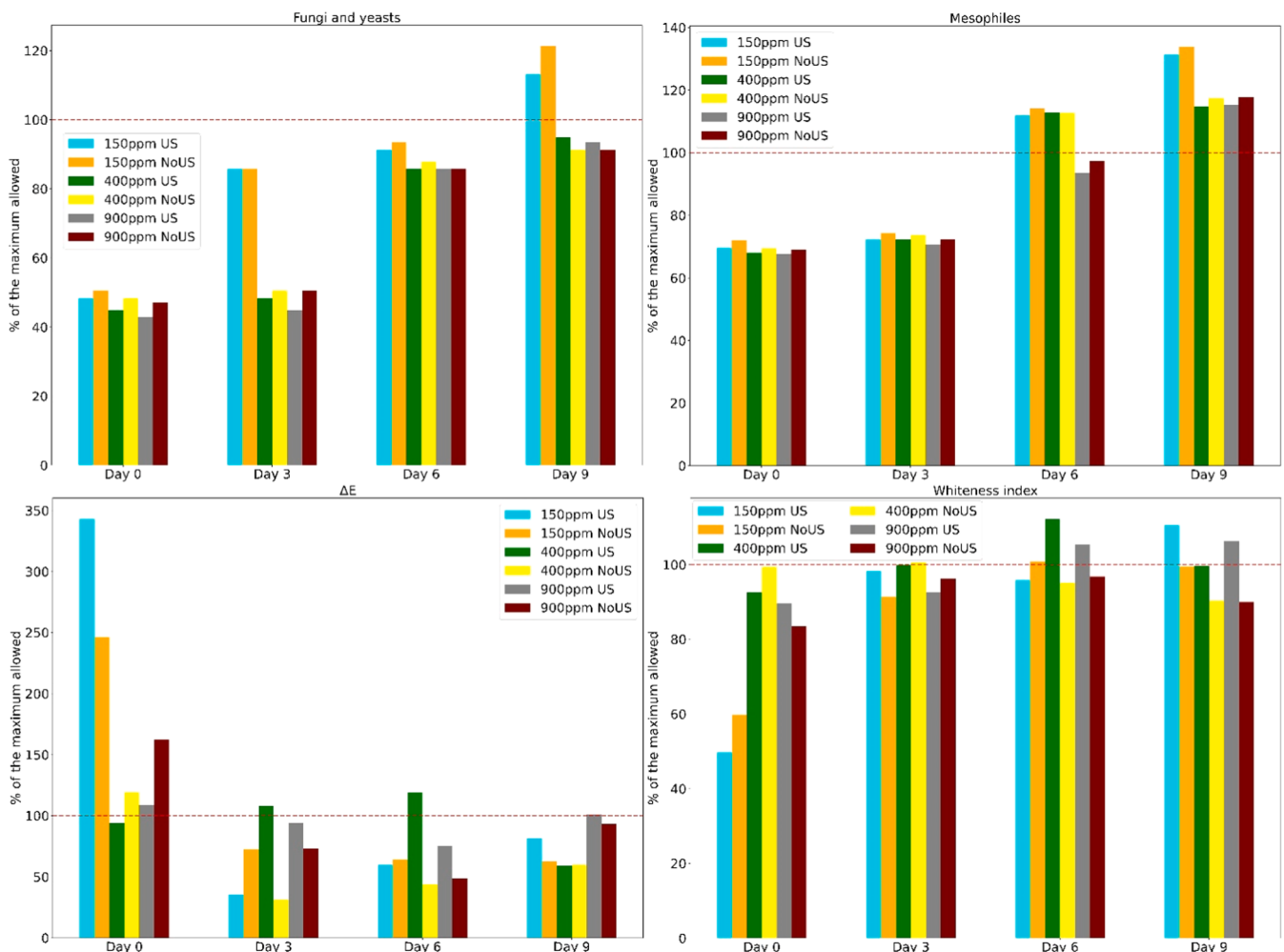


Fig. 8. Evaluation and management of microbiological and color analysis of carrot: a) Fungi and yeasts, b) Mesophiles, c) ΔE , and d) Whiteness index.

concentrations and technologies must be considered for the full analysis of the problem.

Fig. 8 shows the microbiological evaluation (fungi, yeasts, and mesophilic) and sensory (ΔE , and WI) aspects of the carrot after the treatment. For analyzing the range of color in carrots, the values of L^* , a^* , and b^* of the control sample (control), being the fresh untreated sample (L^* of 49.85, a^* of 33.59, and b^* of 40.05), are taken and compared with the values of these parameters for the treated samples. In this case, the values of the parameters L^* , a^* , and b^* are converted to values of the total color change (ΔE): values of ΔE above 5 are defined as perceptible changes between the control sample and the treated one. Another metric related to color is the whiteness index (WI). In this case, 100 is the maximum whiteness and 0 is the minimum. WI is compared with the value of WI of the control sample (27.56). For optimal Colony Forming Unit (microorganism) ranges, the total microbial count in minimally processed vegetables is generally known to be in the range of 3.0–6.0 Log₁₀ CFU/g after processing (Ragaert et al., 2004). A commercially viable product's maximum microbial load is around 10⁷ CFU/g (7.0 Log₁₀ CFU/g).

In Fig. 8, the previously mentioned parameters are represented for the different case studies evaluated in this work. They are presented in % being 100 % the maximum allowed value for the metric (dotted line). Therefore, if the value of one of the parameters is above the dotted line, the carrots after treatment do not meet the microbial or sensory requirements. The results show that the immersion of carrots at concentrations of 900 ppm with and without US technology are those that succeed in reducing microbial growth to a maximum of 6/9 days (Figs. 8a and 8b). Both the ΔE and WI (Figs. 8c and 8d) show that high concentrations manage to extend sensory aspects for up to six days. While low and medium concentrations (150 and 400 ppm) reach up to three days of preservation.

In general, experimental and optimization analysis show that, regardless of the concentration of citric acid or the use of the US technology, the full microbial or color requirements are not met during the 9 days after the carrot treatment. That is, at no concentration situation with or without the use of US technology, the life of the carrot reaches the nine analyzed days; being six days the maximum number that a carrot is preserved with all its properties at concentrations of 900 ppm with and without US technology. During day zero, for practically all citric acid concentrations and US technologies, ΔE does not comply with the maximum selected value according to Fig. 8c. Carrots, when they are initially absorbing citric acid and water, show a change of coloration, which alters the measurement of ΔE at the beginning. However, the value returns to acceptable values in the course of days. Therefore, this change in the color of the carrot could be assumed since, when the carrot is marketed, the values of ΔE will be in the proposed range. The economic and environmental aspects, however, are not the best for high concentrations of citric acid (900 ppm), where compliance with the microbial or sensory parameters is maximized. In particular, those without the use of US technology result in the highest total annual cost of 45.8 [MM\$/y] and an Eco-indicator99 of 4109 [P/y].

Concentrations of 400 ppm with and without US technology are not suitable for carrot preservation since they are economically expensive. These concentrations do not solve microbial growth and sensory issues and have a high environmental impact. Therefore, it can be concluded that the use of low concentrations of citric acid and using US technology is somewhat comparable to the use of high concentrations of citric acid without the use of US technology. However, the use of US technology tends to increase the cost and environmental impact, so a high concentration of citric acid is the better option, as evidenced by the results of the optimization.

3.5. Comparison with similar studies

The application of citric acid and US technology for postharvest preservation has been extensively explored in previous studies. Yilmaz

and Bilek, (2018) demonstrated that ultrasound-assisted vacuum impregnation with natural phenolic compounds from black carrots significantly inhibited microbial growth and maintained the quality of fresh-cut apple slices, showcasing the potential of combining ultrasound with active compounds for extending the shelf life of fresh produce. Similarly, Yuting et al., (2013) highlighted the effectiveness of power ultrasound in preserving fruits and vegetables by reducing decay incidence, improving safety, and maintaining nutritional and sensory quality. These findings align with the current study's results, where US enhanced citric acid absorption and reduced microbial loads in carrots.

Valenzuela (2023) provided a broader perspective on innovative postharvest preservation technologies, emphasizing that methods such as US improve shelf life while maintaining food quality. This study further supports the role of US in achieving effective preservation, particularly when combined with high concentrations of citric acid (900 ppm), which resulted in superior microbial load reduction and sensory quality during the initial storage period.

However, consistent with these studies, the effectiveness of these treatments varies depending on the type of produce and treatment parameters. Factors such as tissue structure, moisture content, and surface porosity significantly influence the outcomes. Furthermore, the increased environmental impact associated with US technology, as noted in this study, highlights the need for balancing effectiveness with sustainability considerations.

By comparing these findings with prior research, the advantages and limitations of citric acid and US technology are evident. While these methods demonstrate significant potential for enhancing postharvest preservation, their application should be tailored to the specific characteristics of each type of produce to optimize results while minimizing costs and environmental impacts.

3.6. Potential applications and future research directions

This study demonstrated the efficacy of citric acid and US technology in enhancing postharvest preservation of carrots, providing a framework for broader application in produce preservation. The insights gained, particularly regarding citric acid absorption, microbial load reduction, and color stability, can inform the adaptation of these methods to other types of produce. Vegetables such as cucumbers, bell peppers, and zucchinis, which share similar structural characteristics and moisture content, represent promising candidates for future research.

Adapting these treatments to other vegetables will require detailed investigations into their tissue properties, including porosity, moisture dynamics, and biochemical composition. These factors are critical in determining acid diffusion rates and the effectiveness of microbial load reduction. Furthermore, exploring the scalability of these methods for commercial applications across various produce types is essential to establish their broader feasibility.

A comprehensive evaluation of sensory attributes, including texture, flavor, and appearance, is another crucial area of focus. While this study provided insights into immediate changes in color parameters, further research should include long-term sensory assessments to ensure consumer acceptance. Additionally, assessing the biochemical and physiological responses of treated produce during extended storage will help uncover potential secondary effects of citric acid and US treatments, ensuring their compatibility with market demands.

This study advances the understanding of postharvest preservation in carrots, its methodology and findings offer a foundation for extending these technologies to a wider range of produce. Future work should integrate detailed sensory and biological evaluations, along with optimization for diverse vegetable types, to achieve practical, sustainable, and broadly applicable postharvest solutions. This approach aligns with the overarching goal of minimizing food loss and enhancing the quality and longevity of fresh produce in global supply chains.

4. Conclusions

The study provides valuable insights into the effects of citric acid concentration and ultrasound (US) technology on carrot preservation. The findings highlight significant aspects related to acid absorption, moisture content, color changes, microbiological load, economic cost, environmental impact, and overall preservation effectiveness. Additionally, the study offers a foundation for broader applications of these methods in food preservation systems.

- **Citric Acid Absorption:** Higher concentrations of citric acid (900 ppm), especially when combined with US technology, result in faster and more substantial acid absorption in carrot tissues. This accelerated absorption suggests potential applicability to other vegetables with similar structural properties.
- **Moisture Content:** The moisture content of carrots increases with longer immersion times and higher citric acid concentrations. Ultrasound further enhances water transfer from the immersion solution to the carrot tissue, facilitating acid diffusion.
- **Color Changes:** Both citric acid concentration and US technology significantly affect carrot color, increasing luminosity and altering red and yellow hues. The changes in color parameters are noticeable but remain within acceptable sensory limits for most treatments.
- **Microbiological Load:** High citric acid concentrations (900 ppm) with US technology effectively reduce fungal and bacterial loads during the initial storage period. However, the treatment effectiveness decreases after six days, requiring additional strategies for longer shelf life.
- **Economic Cost:** Lower citric acid concentrations (150 ppm) are more cost-effective, while higher concentrations (900 ppm) provide better preservation results. The integration of US technology increases processing costs, emphasizing the need to balance effectiveness and affordability.
- **Environmental Impact:** US technology increases the environmental footprint due to higher energy consumption. Lower citric acid concentrations without US are more environmentally friendly, making them suitable for applications where sustainability is a priority.
- **Preservation Limitations:** None of the treatments extend preservation beyond six days in terms of microbiological and sensory quality. This limitation indicates the need for complementary preservation methods or additional research to prolong shelf life.
- **Recommendation:** High concentrations of citric acid without US offer the best balance between effectiveness, cost, and environmental impact. Further research into sensory and biological effects is necessary for a comprehensive evaluation.
- **Broader Applicability:** Although this study focuses on carrots, the approach could be adapted to other vegetables, depending on factors such as tissue porosity, initial moisture content, and microbial load. Future research should explore these variables to determine the broader applicability of citric acid and US treatments.
- **Implications for Sustainable Food Systems:** This study contributes to the development of more sustainable postharvest processing methods by identifying strategies that optimize effectiveness, cost, and environmental impact. The insights gained can help reduce postharvest losses, extend the availability of fresh produce, and improve food security.

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CRediT authorship contribution statement

Segovia-Hernandez Juan Gabriel: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Conceptualization. **Cerón-García Abel:** Writing – original draft, Formal analysis, Data curation. **Gómez-Salazar Julian Andrés:** Writing – review & editing, Writing – original draft, Supervision, Resources, Formal analysis, Data curation, Conceptualization. **Sánchez Antonio:** Writing – original draft, Software, Data curation. **Ramírez-Márquez César:** Writing – original draft, Software, Methodology, Formal analysis. **Sánchez-Ramírez Eduardo:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

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References

- Akköse, A., Aktaş, N., 2014. Curing and diffusion coefficient study in pastırma, a Turkish traditional meat product. *Meat Sci.* 96 (1), 311–314. <https://doi.org/10.1016/j.meatsci.2013.07.026>.
- Alegria, C., Pinheiro, J., Gonçalves, E.M., Fernandes, I., Moldão, M., Abreu, M., 2009. Quality attributes of shredded carrot (*Daucus carota* L. cv. Nantes) as affected by alternative decontamination processes to chlorine. *IFSET* 10 (1), 61–69. <https://doi.org/10.1016/j.ifset.2008.08.006>.
- Alvarenga, V.O., Brito, L.M., Lacerda, I.C.A., 2022. Application of mathematical models to validate emerging processing technologies in food. *Curr. Opin. Food Sci.* 48, 100928. <https://doi.org/10.1016/j.cofs.2022.100928>.
- AOAC. (1997). Official methods of analysis of the Association of Official Analytical Chemists International (16th 384 edition, 3rd revision, Gaithersburg USA).
- Bestultrasonic. (2023). Best Ultrasonic Cleaner: (<https://www.bestultrasonic.co.uk/288-ltr-industrial-ultrasonic-cleaning-bath-280-p.asp>).
- Bhargava, N., Mor, R.S., Kumar, K., Singh Sharanagat, V., 2020. Advances in application of ultrasound in food processing: A review. *Ultrason. Sonochem.*, 105293 <https://doi.org/10.1016/j.ulsonch.2020.105293>.
- Condurso, C., Cincotta, F., Tripodi, G., Merlino, M., Giarratana, F., Verzera, A., 2020. A new approach for the shelf-life definition of minimally processed carrots. *Postharvest Biol. Technol.* 163, 111138. <https://doi.org/10.1016/j.postharvbio.2020.11.11>.
- Ding, T., Ge, Z., Shi, J., Xu, Y.-T., Jones, C.L., Liu, D.-H., 2015. Impact of slightly acidic electrolyzed water (SAEW) and ultrasound on microbial loads and quality of fresh fruits. *LWT-Food Sci. Technol.* 60 (2), 1195–1199. <https://doi.org/10.1016/j.lwt.2014.09.012>.
- Farid, M.M., 2010. *Mathematical modeling of food processing* (First Edition). CRC Press, USA.
- Gabaldón, L.C., Quintero, R.A., Barnard, J., Balandrán, Q.R., Talamás, A.R., Jiménez, C. J., 2007. Effect of ultrasound on the mass transfer and physical changes in brine bell pepper at different temperatures. *J. Food Eng.* 81, 374–379. <https://doi.org/10.1016/j.jfoodeng.2006.11.011>.
- Gallo, M., Ferrara, L., Naviglio, D., 2018. Application of Ultrasound in Food Science and Technology: A Perspective. *Foods* 7 (10), 164. <https://doi.org/10.3390/foods7100164>.
- Gebreslassie, B.H., Guillén-Gosálbez, G., Jiménez, L., Boer, D., 2009. Design of environmentally conscious absorption cooling systems via multi-objective optimization and life cycle assessment. *Appl. Energy* 86 (9), 1712–1722. <https://doi.org/10.1016/j.apenergy.2008.11.019>.
- Ghafoor, M., Misra, N.N., Mahadevan, K., Tiwari, B.K., 2014. Ultrasound assisted hydration of navy beans *Phaseolus vulgaris*. *Ultrason. Sonochem.* 21, 409–441. <https://doi.org/10.1016/j.ulsonch.2013.05.016>.
- Goli, T., Bohuon, P., Ricci, J., Trystram, G., Collignan, A., 2011. Mass transfer dynamics during the acidic marination of turkey meat. *J. Food Eng.* 104 (1), 161–168. <https://doi.org/10.1016/j.jfoodeng.2010.12.010>.
- Gómez, J., Sanjuán, N., Arnau, J., Bon, J., Clemente, G., 2019. Modeling of sodium nitrite and water transport in pork meat. *J. Food Eng.* 249, 48–54. <https://doi.org/10.1016/j.jfoodeng.2019.01.008>.
- Gómez-Salazar, J.A., Ochoa-Montes, D.A., Cerón-García, A., Ozuna, C., Sosa-Morales, M. E., 2018. Effect of Acid Marination Assisted by Power Ultrasound on the Quality of Rabbit Meat. *J. Food Qual.* 2018, 1–6. <https://doi.org/10.1155/2018/5754930>.
- Gómez-Salazar, J.A., Patlán-González, J., Sosa-Morales, M.E., Segovia-Hernandez, J.G., Sánchez-Ramírez, E., Ramírez-Márquez, C., 2022. Multi-objective optimization of

- sustainable red prickly pear (*Opuntia streptacantha*) peel drying and biocompounds extraction using a hybrid stochastic algorithm. *FBP* 2022, 155–166. <https://doi.org/10.1016/j.fbp.2022.01.003>.
- Hernández-Carranza, P., Ruiz-López, I.I., Pacheco-Aguirre, F.M., Guerrero-Beltrán, J.Á., Ávila-Sosa, R., Ochoa-Velasco, C.E., 2016. Ultraviolet-C light effect on physicochemical, bioactive, microbiological, and sensorial characteristics of carrot (*Daucus carota*) beverages. *Food Sci. Technol. Int* 22 (6), 536–546. <https://doi.org/10.1177/1082013216631646>.
- Hiranvarachai, B., Devahastin, S., Chiewchan, N., 2011. Effects of acid pretreatments on some physicochemical properties of carrot undergoing hot air drying. *FBT* 89 (2), 116–127. <https://doi.org/10.1016/j.fbp.2010.03.010>.
- Kato-Noguchi, H., Watada, A.E., 1997. Citric acid reduces the respiration of fresh-cut carrots. *Hortic. Sci.* 32, 136–144.
- Khaire, R.A., Bhaskar, N.T., Gogate, P.R., 2022. Applications of ultrasound for food preservation and disinfection: A critical review. *J. Food Process. Preserv.* 1, e16091. <https://doi.org/10.1111/jfpp.16091>.
- Marier, J., Boulet, M., 1958. Direct Determination of Citric Acid in Milk with an Improved Pyridine-Acetic Anhydride Method. *Journal of Dairy Science* 41, 1683. [https://doi.org/10.3168/jds.S0022-0302\(58\)91152-4](https://doi.org/10.3168/jds.S0022-0302(58)91152-4).
- Miano, A.C., Ibarz, A., Augusto, P.E.D., 2016. Mechanisms for improving mass transfer in food with ultrasound technology: Describing the phenomena in two model cases. *Ultrason. Sonochem.* 29, 413–419. <https://doi.org/10.1016/j.ultsonch.2015.10.020>.
- Miao, Y., Chen, C., Ma, Q., Wang, Y., Zhang, X., Guo, F., Yong, B., 2014. Effects of Soaking with Natural Additives in Combinations with Vacuum or Modified Atmosphere Packaging on Microbial Populations and Shelf Life of Fresh Truffles (*Chinese Tuber Indicum*). *J. Food Sci.* 79 (10), M2040–M2047. <https://doi.org/10.1111/1750-3841.12651>.
- Nikitenko, S.I., Chemat, F., 2015. *Green Process Engineering: From Concepts to Industrial Applications. Ultrasound in process engineering*. CRC Press, Boca Raton, Florida, USA, pp. 145–165.
- NOM-092-SSA1-1994. NORMA Oficial Mexicana, Bienes y servicios. Método para la cuenta de bacterias aerobias en placa.
- NOM-111-SSA1-1994. NORMA Oficial Mexicana, Bienes y servicios. Método para la cuenta de mohos y levaduras en alimentos.
- Phong, W.N., Payne, A.D., Dykes, G.A., Coorey, R., 2023. Postharvest decontamination of fresh black truffle (*Tuber melanosporum*): Effects on microbial population and organoleptic qualities. *Postharvest Biol. Technol.* 197, 112191. <https://doi.org/10.1016/j.postharvbio.2022.112191>.
- Piscopo, A., Zappia, A., Princi, M.P., De Bruno, A., Araniti, F., Antonio, L., Poiana, M., 2019. Quality of shredded carrots minimally processed by different dipping solutions. *J. Food Sci. Technol.* 56, 2584–2593. <https://doi.org/10.1007/s13197-019-03741-6>.
- Ragaert, P., Verbeke, W., Devlieghere, F., Debevere, J., 2004. Consumer perception and choice of minimally processed vegetables and packaged fruits. *Food Qual. Prefer* 15 (3), 259–270. [https://doi.org/10.1016/S0950-3293\(03\)00066-1](https://doi.org/10.1016/S0950-3293(03)00066-1).
- Rahman, S., Jin, Y., Oh, D., 2011. Combination treatment of alkaline electrolysed water and citric acid with mild heat to ensure microbial safety, shelf-life and sensory quality of shredded carrots. *Food Microbiol* 28 (3), 484–491. <https://doi.org/10.1016/j.fm.2010.10.006>.
- Ramirez, D.O.S., Carletto, R.A., Tonetti, C., Giachet, F.T., Varesano, A., Vineis, C., 2017. Wool keratin film plasticized by citric acid for food packaging. *Food Packag* 12, 100–106. <https://doi.org/10.1016/j.fpsl.2017.04.004>.
- Sagong, H.-G., Lee, S.-Y., Chang, P.-S., Heu, S., Ryu, S., Choi, Y.-J., Kang, D.-H., 2011. Combined effect of ultrasound and organic acids to reduce *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* on organic fresh lettuce. *Int. J. Food Microbiol.* 145 (1), 287–292. <https://doi.org/10.1016/j.ijfoodmicro.2011.01.01>.
- São José, J.F.B., Vanetti, M.C.D., 2012. Effect of ultrasound and commercial sanitizers in removing natural contaminants and *Salmonella enterica* Typhimurium on cherry tomatoes. *Food Control* 24 (1–2), 95–99. <https://doi.org/10.1016/j.foodcont.2011.09.008>.
- São José, J.F.B., Andrade, N.J., de, Ramos, A.M., Vanetti, M.C.D., Stringheta, P.C., Chaves, J.B.P., 2014. Decontamination by ultrasound application in fresh fruits and vegetables. *Food Control* 45, 36–50. <https://doi.org/10.1016/j.foodcont.2014.04.015>.
- Sayyaadi, H., 2020. *Modeling, assessment, and optimization of energy systems*. Academic Press, Elsevier, pp. 327–459.
- SIAP. (2023). *Agrifood Outlook 2022/2023*. Retrieved from Agri-Food and Fisheries Information Service (SIAP): (https://nube.siap.gob.mx/gobmx_publicaciones_siap/).
- Silva, V.L., Sanjuán, N., 2019. Opening the black box: a systematic literature review of life cycle assessment in alternative food processing technologies. *J. Food Eng.* 250, 33–45. <https://doi.org/10.1016/j.jfoodeng.2019.01.010>.
- Siucińska, K., Konopacka, D., 2014. Application of Ultrasound to Modify and Improve Dried Fruit and Vegetable Tissue: A Review. *Dry. Technol.* 32 (11), 1360–1368. <https://doi.org/10.1080/07373937.2014.916719>.
- Tiwari, A., Singh, G., Sharma, V., Srivastava, R.K., Sharma, S., 2021. Harnessing the potential of UVB irradiation for improving the nutraceutical properties of edible xylophilic mushroom dried powder. *LWT* 150, 111913. <https://doi.org/10.1016/j.lwt.2021.111913>.
- Turton, R., Bailie, R.C., Whiting, W.B., Shaeiwitz, J.A., Bhattacharyya, D., 2012. *Analysis, Synthesis and Design of Chemical Processes*. Pearson Education.
- Valenzuela, J.L., 2023. Advances in postharvest preservation and quality of fruits and vegetables. *Foods* 12 (9), 1830. <https://doi.org/10.3390/foods12091830>.
- Virto, R., Sanz, D., Álvarez, I., Condón, Raso, J., 2005. Inactivation kinetics of *Yersinia enterocolitica* by citric and lactic acid at different temperatures. *Int. J. Food Microbiol.* 103 (3), 251–257. <https://doi.org/10.1016/j.ijfoodmicro.2004.11.01>.
- Wang, J., Cui, Z., Li, Y., Cao, L., Lu, Z., 2020. Techno-economic analysis and environmental impact assessment of citric acid production through different recovery methods. *J. Clean. Prod.* 249, 119315. <https://doi.org/10.1016/j.jclepro.2019.119315>.
- Yilmaz, F.M., Bilek, S.E., 2018. Ultrasound-assisted vacuum impregnation on the fortification of fresh-cut apple with calcium and black carrot phenolics. *Ultrason. Sonochem.* 48, 509–516. <https://doi.org/10.1016/j.ultsonch.2018.07.007>.
- Yuting, X., Lifan, Z., Jianjun, Z., Jie, S., Xingqian, Y., Donghong, L., 2013. Power ultrasound for the preservation of postharvest fruits and vegetables. *Int. J. Agric. Biol. Eng.* 6 (2), 116–125.
- Zhang, H., Wang, S., Goon, K., Gilbert, A., Nguyen Huu, C., Walsh, M., Nitin, N., Wrenn, S., Tikekar, R.V., 2020. Inactivation of foodborne pathogens based on synergistic effects of ultrasound and natural compounds during fresh produce washing. *Ultrason. Sonochem.* 64, 104983. <https://doi.org/10.1016/j.ultsonch.2020.104983>.