Current Research in Food Science 5 (2022) 313–324

Contents lists available at ScienceDirect

Current Research in Food Science

journal homepage: www.sciencedirect.com/journal/current-research-in-food-science

Non-thermal hydrodynamic cavitation processing of tomato juice for physicochemical, bioactive, and enzyme stability: Effect of process conditions, kinetics, and shelf-life extension

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ARTICLE INFO

Keywords:
Hydrodynamic cavitation
Tomato juice
Bioactive compounds
Pectin methyl esterase
Viscosity
Fuzzy logic

ABSTRACT

Fresh tomato juice was processed by hydrodynamic cavitation (HC) at 5 to 15 psi pressures for 5–30 min. A full factorial design was applied to optimize the HC treatment of tomato juice quality. Optimal conditions were recorded at 10 psi for 10 min, which showed no significant ($p < 0.05$) change in lycopene content to that of freshly obtained unprocessed tomato juice (control). After processing, the retention of 93% ascorbic acid and 96.6% of total phenolic compounds (TPC) was observed. Similarly, sedimentation and viscosity were mildly affected by HC processing (89.2 and 94.4% of values in the treated sample, respectively). While pH, total soluble solids (TSS), titratable acidity (TA) of HC treated sample remained unchanged ($p < 0.05$). The results were also compared with the conventional thermally processed tomato juice (90 °C for 90 s). Although thermal treatment resulted in the inactivation of 92.2% of pectin methylesterase and a 5 log reduction in total plate counts, it also showed significant reductions in ascorbic acid (61.4%), TPC (72.3%), and physical properties (37.7% of SI and 83.2% viscosity). However, HC processing could achieve a maximum of 4.9% inactivation of PME and 1 log reduction at high treatment conditions, respectively (15 psi for 30 min). The shelf-life study showed more retention of bioactives and better physicochemical properties in tomato juice samples stored at 4 °C for 15 days than the control. Sensory evaluation revealed that the overall acceptability of the optimized HC treated (0.714) sample was better than the thermally treated sample (0.591). The observed results concluded that HC-treated tomato juice was comparatively better than thermally-treated tomato juice in retaining bioactive compounds. Consequently, HC constitutes a promising approach in food processing to improve and retain the beneficial properties of tomato juice.

1. Introduction

Tomatoes are a good source of vitamin A, B, and C, minerals (calcium, magnesium, phosphorous, potassium, zinc, manganese, sodium, potassium), lycopene, and other bioactive constituents. The most beneficial feature of tomatoes is the level of antioxidant activity contributed by lycopene (Salehi et al., 2019). The long-chain diene structure in lycopene is capable of quenching the singlet oxygen and preventing the cell from damage. The polyene structure in carotenoids can exist in both isomeric forms, cis and trans. However, during tomato juice processing and storage conditions, the bioactivity content of lycopene is lowered and becomes susceptible to oxidation due to *trans*-to-*cis* isomerization. The heat stress developed within the system as a response to the thermal process to achieve stability is the reason for the change in geometrical isomerization (Cole and Kapur, 1957). Thermal treatment of tomato puree at 100 °C for 20 min resulted in 20% loss of lycopene (Luterotti et al., 2015). Decimal reduction time of lycopene was calculated, and it was reported that 90% of lycopene was lost when it was processed at 100 °C for 75 min (Manzo et al., 2019).

The nutritional quality of tomato juice is predominantly related to ascorbic acid and lycopene, a constituent responsible for the native red color in tomato juice. Ascorbic acid is a highly reactive compound and is degraded when subjected to heat, oxidation reaction, and free radical generation during processing (Hsu, 2008). Generally, tomato products' sensory quality and marketability are directly related to the final products' color, consistency, and flavor (Gould, 1978). The consistency and stability of the product is influenced by viscosity and cloud value. Cloud value refers to the particles suspended in fluids due to brownian

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https://doi.org/10.1016/j.crfs.2022.01.025
Received 21 July 2021; Received in revised form 19 January 2022; Accepted 31 January 2022
Available online 4 February 2022

motion. Pectin, a primary cell wall component, stabilizes the fruit beverage and provides viscosity to the final product.

Thermal processing is a common technique employed to extend the shelf life of food systems by inactivating enzymes and microbes (Ağçam et al., 2018). However, nutrition, organoleptic characteristics, and antioxidant capacity are lost when thermally processed (Hsu, 2008). Therefore, consumers are now demanding high-quality juices that are convenient, more nutritious, and minimally processed with similar characteristics to fresh juice. The food industry is showing greater interest in novel food processing technologies (Señorans et al., 2003).

Non-thermal technologies such as pulsed electric field (PEF) and high-pressure processing (HPP) have been introduced. These non-thermal techniques can inactivate microorganisms at a minimal loss in bioactive compounds. However, the major drawback of these technologies is the higher operational and investment cost during commercialization.

Hydrodynamic cavitation (HC) is a more recently explored scalable technology in processing fruit juices (Arya et al., 2020; Katariya et al., 2020). Lower equipment and operational costs are the significant advantages of adopting such novel technology in fruit juice processing (Randhavane Shrikant and Khambete, 2017). During HC, vaporization, bubble generation, and bubble implosion causes due to pressure variation in the fluid flow (Randhavane Shrikant and Khambete, 2017). Further, it leads to severe localized pressure and temperature environments termed as *"hot spots"* along with strong shear and turbulence, shock waves, and free radical generation causing the protein (enzymes) hydrolysis and cleavage of the microbial cell (Arya et al., 2021). Recently, the application of HC during the processing of orange juice resulted in the retention of bioactive compounds, and at the same time, successful inactivation of PME enzyme (Abid et al., 2013).

Further, the effect of cavitation in blueberry puree application favored desirable changes during processing and helped to inactivate microorganisms and quality deteriorating enzymes of peroxidase and polyphenol oxidases (Fan et al., 2018; Martynenko and Chen, 2016). The loss of bioactive (lycopene and ascorbic acid) in tomato juices is majorly due to thermal degradation. Since the HC processing creates tiny hot spots with minimal temperature rise, resulting in more bioactive compounds retention. Further research is needed to understand the potential of this technique concerning fruit juice.

Therefore, present work was carried out to optimize HC process parameters for maximum nutrient retention and more fresh-like attributes in tomato juice and characterize and compare the optimized HC vs. conventionally treated tomato juice in terms of their physical, chemical, nutritional, and sensory properties. Further, an attempt was made to evaluate the shelf life of HC and thermally processed tomato juice during a storage period of 15 days at 4 °C.

2. Materials and methods

2.1. Materials

Fresh red tomatoes of uniform size, appearance, and color were procured from the Sahakari Bhandar market, Mumbai. All required chemicals were ensured to be analytical grade and procured from Himedia, Mumbai, India.

2.2. Tomato juice preparation

Tomatoes were washed and chopped before juicing. Fresh juice was extracted using a pulper (HL7701/00 Mixer 109Grinder, Philips, India) at 6000 rpm for 4–5 min. Obtained juice was filtered through stainless steel mesh (5 °Brix) with a mesh size of 100 μm. Extracted juice was stored in dark brown glass bottles maintained at 4 °C before analysis.

2.3. HC setup and tomato juice processing

The hydrodynamic cavitation setup was purchased from Zero-d Industries Pvt. Ltd., Mumbai, India. The setup includes a holding tank with 2L capacity volume, a positive displacement (reciprocating) 0.5 HP pump with a variable frequency drive that can attain a maximum pressure of 15 psi. Cavitation was carried out by a centrifugal pump by passing 1000 mL of freshly squeezed tomato juice through a venturi meter (throat diameter of 5 mm) HC unit (Fig. 1). The effect of cavitation was created with varying inlet pressure from 5 to 15 psi by adjusting the opening and closing of the valves. Experiments were conducted at all the possible combinations of experimental runs for each pressure level and treatment time at 5, 10, 15, 20, 25, and 30 min. The cavitation number ranged from 0.67 to 0.94 for different pressure time combinations. During HC treatment, heat generated from the mechanical pump and cavitation caused the rise in temperature in tomato juice. The temperature of every sample was recorded using a digital thermometer both before and after treatment. The increase in temperature for each pressure time combination and the heat energy dissipated into the system is illustrated in Fig. S1 (a and b). Treated samples were stored under refrigeration conditions (4 °C) for subsequent analysis. The initial temperature of tomato juice was 23 ± 2 °C. At the end of the HC treatment, the maximum rise in the temperature of tomato juice was recorded to be 47 ± 2 °C.

2.4. Heat treatment of tomato juice

The pasteurization of tomato juice was done at 90 °C for 92 s treatment condition. This time-temperature combination was selected for achieving a minimum 5 log reduction of total plate count in tomato juice (Min et al., 2003). The thermal treatment was carried out using a thermostatic water bath maintained at 90 °C. The sample was filled inside 20-mL LDPE pouches of thickness 80 μm and was placed in a water bath. The come-up time to reach 90 °C, i.e., to the core temperature of the pouch, was noted down (approx. 3 mins). After the come-up time, the sample was treated at 90 °C for 92 s. After the treatment, the sample was immediately stored at 4 °C.

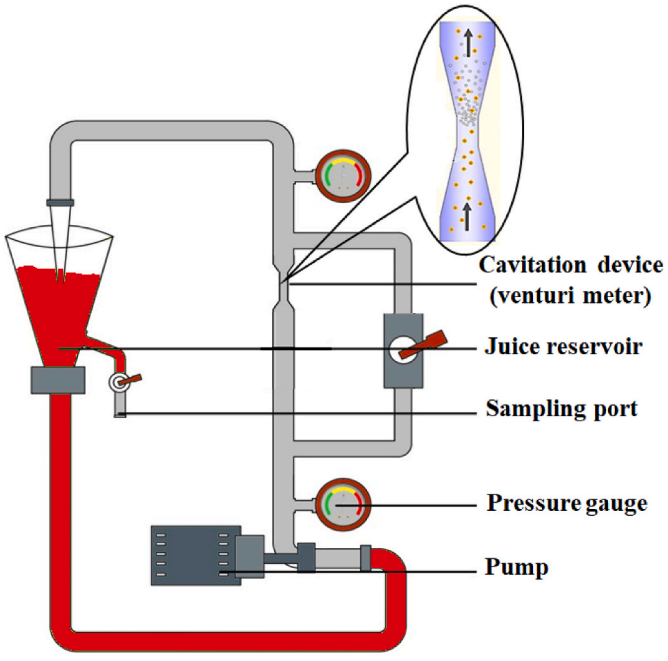

Fig. 1. Schematic representation of hydrodynamic cavitation for tomato juice processing.

2.5. Experimental design

The effect of HC parameters, i.e., pressure and time, on dependent variables (responses), was evaluated through empirical mathematical modeling. The dependent parameters chosen were pH, TSS, titratable acidity, viscosity, sedimentation index, particle size distribution, lycopene content, ascorbic acid, total phenolic compounds, and PME activity. The full factorial design was used to optimize the experimental conditions. The pressure was applied at five levels (5, 7.5, 10, 12.5, 15 Psi) for 6 discrete lengths of time (5–30 min at 5 min intervals). The full factorial design gave 30 combinations of experimental trials, and data were analyzed for each trial condition, and the data is presented in Table S1 (supplementary data). Design expert software (V.12, Stat-Ease Inc., Minneapolis, USA) was chosen for performing experimental design, data analysis, and regression modeling (Eq. (1))

$$y = x_1^2 + x_2^2 + \beta x_1 + x_2 + x_1 x_2 + c \quad (1)$$

2.6. Measurement of pH, titratable acidity (TA), and total soluble solids (TSS)

The pH, titratable acidity (TA), and total soluble solids (TSS) was determined as per the standard protocols (Ranganna, 1986; Solunke et al., 2018). The digtal pH meter was used to determine the pH (Model: HI 2215, Hanna benchtop pH meter, HANNA® instruments). The pH meter was calibrated with commercial buffer solutions of pH 7.0 and pH 4.0. The pH meter's probe was dipped in 20 mL of juice kept in a 30 mL beaker, and pH was recorded at 29 ± 2 °C. Total soluble solids were determined using a benchtop refractometer (Model: ARM-2s, Benchtop Digital Abbe Refractometer, Aczet Thailand Co. Ltd.). 2–3 drops of tomato juice were placed on the refractometer prism, then °brix was measured at 29 ± 2 °C. After each analysis refractometer prism was cleaned with distilled water. Titratable acidity was analyzed by dissolving 10 mL of sample in 90 mL distilled water. 2–3 drops of phenolphthalein indicator were added to mark the endpoint. The diluted sample was titrated against the standardized solution of 0.1 N NaOH. The volume of NaOH consumed was noted down, and percent titratable acidity was calculated using Equation (2). Milliequivalent factor for tomato juice was found out to be 0.064, with malic acid being predominant.

$$\%\ TA = \frac{(ml\ of\ NaOH\ used)x\ 0.1\ N\ NaOH\ x\ milliequivalent\ factor\ x\ 100}{grams\ of\ sample} \quad (2)$$

2.7. Measurement of color

The measurement of the color profile was done using HunterLab colorimeter (LabScan XE, Hunter Associates Laboratory, USA) to find the L*, a*, b* color values based on the CIE scale. The total color difference ΔE* was calculated using Eq. (3), from L* (dark to lightness), a* (green to red), and b* (blue to yellow) values. The instrument was calibrated using white and black tiles. 80 mL sample was taken in a quartz cuvette and placed above the light source in the colorimeter and was covered with a black cover. Triplicates were performed, and L*, a*, b* were recorded (Eq. (3)).

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (3)$$

2.8. Measurement of sedimentation index (SI)

Juice samples were filled in 15 mL graduated centrifuge tubes to estimate the sedimentation level after 14 days of storage maintained at 4 °C. Using Equation (4), the sedimentation index was calculated (Serdula et al., 1996).

$$Sedimentation \cdot Index \cdot (\%) \cdot = \cdot \frac{Sedimentation\ volume}{Total\ volume\ of\ sample} X100\% \quad (4)$$

2.9. Measurement of apparent viscosity

The apparent viscosity of tomato juice samples was measured using Brookfield© Rheometer (Model: DV-III, Brookfield Engineering Labs Inc., US). During measurement, the temperature was maintained at 25±0.2 °C. The spindle (S-61) with concentric cylinder geometry was rotated at 150 rpm. Before the analysis, the spindle was submerged in the sample and rotated to reach thermal equilibrium after 2min. The readings were expressed as centipoises (cP).

2.10. Measurement of particle size

The average diameter of juice sample particles was analyzed using particle size analyzer Mastersizer 2000 (Malvern Instruments, Malvern, U.K.). The fluctuations were detected, and particle size was calculated and expressed in μm with the software provided along with the instrument.

2.11. Measurement of bioactive compounds

2.11.1. Measurement of lycopene content in tomato juice

Lycopene in tomato juice was evaluated by following the procedure of Munde et al. (2017). 1 g of tomato juice was added to the beaker, and later 40 mL of ethanol and 30 mL of hexane solution were added for extraction during 10 min time. Subsequently, 2 mL of distilled water was added, and phase separation was observed after 10 min. For analysis, supernatant, i.e., hexane layer, was collected and analyzed at 503 nm in UV- spectrophotometer (Model: UV1700; Make: Shimadzu, Japan). From equation (5), lycopene content was calculated and expressed as (mg/kg).

$$Lycopene \cdot (mg/kg) \cdot = \cdot \frac{A503nm \times MW \times V}{WS \times \xi} \quad (5)$$

where A_{503} nm is the absorbance of hexane layer, MW is the molecular weight of lycopene, V is the volume of supernatant (2.7 mL), WS is the sample weight (1g), ξ is the extinction coefficient for lycopene in hexane (1.72×10^{-5} L mol^{-1} cm^{-1}) at 503 nm.

2.11.2. Measurement of ascorbic acid in tomato juice

Tomato juice was diluted with 2% of metaphosphoric acid (w/v) with a ratio of 1:1 and centrifuged for 10 min at 7871 g force to reduce the effect of interfering substances. The supernatant was collected for analysis. 0.350 mL of supernatant was pipetted into the dry cuvette. To it, 0.650 mL of 2,6-dichlorophenol-indophenol (DCPIP) solution was added, and absorbance was recorded at 518 nm after 3 min of incubation using a UV-spectrophotometer. The color change was observed because of DCPIP dye reduction to a colorless compound by ascorbic acid in the sample (Katariya et al., 2020). The blank consisting of 0.350 mL of 2% HPO_3 and 0.650 mL of distilled water was used to set the instrument with 100% transmittance. L-ascorbic acid was used as standard, and the linear relationship between absorbance and concentration was used to calculate the ascorbic acid remaining in the samples. Ascorbic acid content was expressed as mg/100 ml of tomato juice in Eq (6).

$$Ascorbic \cdot acid \cdot (mg/100\ \ mL) \cdot = \cdot \frac{\Delta Abs_{sample}}{Slope\ of\ standard\ curve} X \frac{df}{Vs} \quad (6)$$

Here, the value ΔAbs_{sample} represents a diluted sample, df as dilution factor, and V_s is the sample volume.

2.11.3. Measurement of total phenolic compounds in tomato juice

Methanolic extraction of tomato juice was prepared by mixing 80%

of methanol in 1:1 ratio for 3hr at room temperature, followed by filtration (More and Arya, 2021). Incubation for 20 min in dark conditions at room temperature was performed for a reaction mixture composed of 100 μL 80% methanol, 100 μL FCR, 100 μL methanolic extract of the diluted sample, and 700 μL of 20% Na_2CO_3. The clear supernatant was collected after incubation, followed by centrifugation at 7871*g* force for 4–5 min. Absorbance was measured at 735 nm using UV-Vis Spectrophotometer. The standard linear relationship was obtained by varying the concentration of gallic acid (20–200 μL/mL), and the color transition to deep blue color was measured at 735 nm after 20 min of incubation in the dark at room temperature. The color change was due to the interaction of phenolic compounds with the alkaline FCR solution. Total phenolic compounds were determined using Eq. (7) and expressed as gallic acid equivalent/100 mL.

$$mg\ GAE \Big/ 100\ ml = \frac{Abs_{sample}}{slope\ of\ standard\ curve} \times \frac{df}{Vs} \times \frac{100}{1000} \tag{7}$$

Here, the value ΔAbs_{sample} describes the absorbance of the sample, dilution factor (d_f), and V_s represents sample volume for analysis.

2.12. Measurement of PME activity in tomato juice

PME Activity in tomato juice was determined according to the method reported previously by Salas-Tovar, (Katariya et al., 2020; Kimball, 1991). In this analysis, the rate of the free carboxyl group formed by the action of PME enzyme in pectin chain compounds was evaluated. Pectin assay was performed by mixing 2% pectin with 1M NaCl solution. Along with 20 mL of pectin assay solution, 5 mL of treated juice sample was mixed using a stirrer with a pH probe inserted. The pH of the solution was adjusted to 7.0 by adding 2N NaOH. Again, the solution pH was readjusted to 7.7 by adding 0.05N NaOH. After reaching pH 7.7, 0.10 mL of 0.05N NaOH was immediately added, and the time required for the pH to return to 7.7 was measured to calculate the PME activity according to Eq (8).

$$\text{PMEU} \cdot = \cdot \frac{V \times N}{v \times t} \tag{8}$$

Where PMEU is pectin methylesterase units per unit volume of tomato juice (meq. H^+ mL^{-1} min^{-1}), V is the volume (mL) of NaOH, N is the normality of NaOH, v is sample volume taken for analysis, and t is time (min). PME inactivation in tomato juice was calculated using Eq. 9

$$PME\ Inactivation\ (\%) = \frac{A_0 - A_t}{A_0} x100 \tag{9}$$

Where A_0 and A_t are the PME activity of control and treated sample of tomato juice at time "t".

The rate constant for the PME inactivation was calculated from the first-order kinetics equation. From the graph plotted between logarithmic residual activity and treatment time, The PME inactivation rate was calculated assuming a first-order kinetics (equation (10). The half-life ($t_{1/2}$) was calculated according to Eq. (11), indicating the time taken to reduce 50% of PME activity to its initial value at respective treatment conditions. The time required to reduce the initial activity by 90% is D_{90} and expressed in Eq. (12).

$$\ln\left(\frac{A_t}{A_O}\right) = -kt \tag{10}$$

$$t_{1/2} = \frac{\ln(2)}{k} \tag{11}$$

$$D = \frac{\ln(10)}{k} \tag{12}$$

2.13. Measurement of total plate count

The total aerobic microbial load was enumerated by adopting the serial dilution method. HC and thermally treated samples of tomato juice were used as inoculate. Inocula were prepared by mixing 10 mL of the treated sample in 90 mL of saline solution (0.85% w/w sodium chloride solution in distilled water). Samples were diluted to 10^{-6} concentrations. A 1 mL of diluted inoculum was pipetted out to sterile petri dishes with nutrient agar. Nutrient agar was prepared and added over the sample following the pour plate method. Plates are incubated for 24h maintained at 37 °C. Microbial cells are enumerated as a colony-forming unit and expressed as N, cfu/mL.

(Eq. (13)) and log reduction was calculated using Eq. (14).

$$N\ \left(\frac{\text{Cfu}}{\text{mL}}\right) = \frac{\left(No.of\ Colonies\ x\ 10^{-2}\right) + \left(No.of\ Colonies\ x\ 10^{-3}\right).}{n} \tag{13}$$

$$Log\ Reduction = \frac{N}{N_0} \tag{14}$$

The term n denotes the number of dilutions and the value N, N0 are the colony-forming units per mL (cfu/mL) in the treated and control sample.

2.14. Shelf-life of HC and thermally treated tomato juice

The shelf-life of HC and thermally treated tomato juice were assessed in samples stored in PET bottles under refrigerated conditions (4 °C). Physical, chemical, and enzyme analyses were carried out after 15 days of storage, and data were analyzed using one-way ANOVA. A Tukey's multiple comparison test was used to identify differences at a level of significance of 95% ($p < 0.05$). Analysis was carried out using SPSS software respectively.

2.15. Sensory evaluation of HC and thermally treated tomato juice using the fuzzy logic methodology

The sensory panel of 8 members was chosen based on their health status, and a product description was provided before conducting analysis. Absolute seven samples were assessed using fuzzy logic. Samples were tagged as S1 (control sample), S2 (10 psi for 5 min), S3 (10 psi for 10 min), S3 (10 psi for 15 min), S4 (10 psi for 20 min), S5 (10 psi for 25 min), S6 (10 psi for 30 min) and S7 (heat-treated; 90 °C for 90 s). Five sensory attributes were selected before analysis based on their relevance for this product and included color, aroma, mouthfeel, taste, and after taste. Sensory scores (SS) of the samples are recorded on the 9-point hedonic scale, and these values are converted into a 5-point linguistic variable (not satisfactory (NS), fair, medium, good, excellent) in the fuzzy logic method. Evaluators were also asked to rank the relative importance of the product's selected quality attribute (QS) in the form of linguistic variable (not at all important, somewhat important, important, highly important, and extremely important). The sensory scale was divided to represent the linguistic variable on a linear scale and Fig. 2 represents the triangular membership function on a sensory scale. Both SS and QS for each sample can be evaluated using the following equation (Eq. (15))

$$SS \Big/ QS = \frac{n_1(triplet\ of\ NS) + n_2(triplet\ of\ fair) \ldots n_5(triplet\ of\ excellent)}{(n_1 + n_2 + n_3 + n_4 + n_5)} \tag{15}$$

Here, *n* represents the number of judges rating the linguistic variable.

To calculate the overall sensory score (OS), the sensory score of the sample (SS) and relative weightage of the quality score (QS_{rel}) were calculated using Eq. (16).

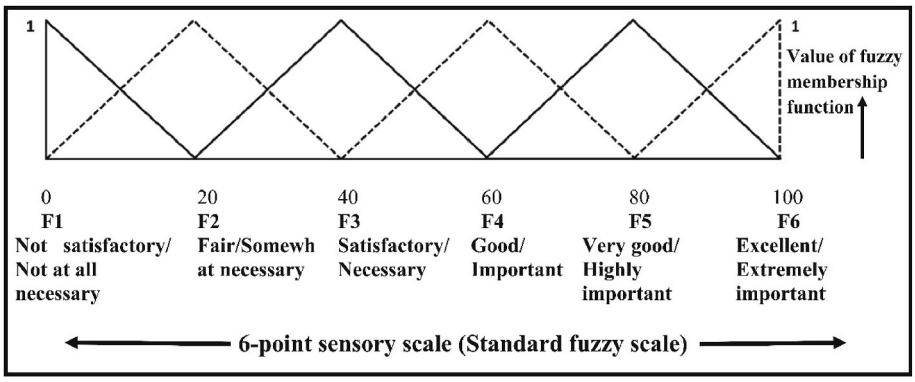

Fig. 2. Standard six-point fuzzy scale for sensory evaluation (values of F1 to F6 are defined by a set of 10 numbers which are the maximum numbers between each two consecutive points from 0 to 100) (Dhar et al., 2021)

$$QS_{Rel} = \frac{QS\ of\ each\ sensory\ attribute}{Q_{Sum}} \tag{16}$$

Where Q_{Sum} is the sum of the first triplet digit in the various quality attribute.

The overall sensory score for each sample can be expressed as

$$OS = (SS_{colour} x\ \ QCrel_{Colour}) + \ldots + (SS_{Aftertaste} x\ \ QCrel_{After\ taste}) \tag{17}$$

A 5-point sensory scale is converted into a 6-point sensory scale to obtain the sensory score with more impression. The membership function of the standard fuzzy scale was evaluated by a set of 10 numbers as shown below (Eq. (18)),

F1= (1,0.5,0,0,0,0,0,0,0,0) F2 = (0.5,1,1,0.5,0,0,0,0,0,0)

F3 = (0,0,0.5,1,1,0.5,0,0,0,0) F4 = (0,0,0,0,0.5,1,1,0.5,0,0)

F5 = (0,0,0,0,0,0,0.5,1,1,0.5) F6 = (0,0,0,0,0,0,0,0,0.5,1) (18)

The overall membership function (B_x) was calculated by separately converting the triplets of OS into a set of ten numbers based on equations given below and the corresponding values of the point x = 10, 20, 30, 40, 50, 60, 70, 80, 90, 100.

$$B_x = \frac{x - (a - b)}{b} \text{ for } (a - b) < x < a \tag{19}$$

$$B_x = \frac{(a + c) - x}{b} \text{ for } a < x < (a + c) \tag{20}$$

$$B_x = 0 \text{ for } x > (a + c) \tag{21}$$

Similarity values (S_m) are an essential and final step that helps identify the linguistic adjective for the given sample. It can be calculated based on the membership function of the sample (B_x) and the membership function of the standard fuzzy scale (F) obtained from equation (22).

$$S_m(F, B) = \frac{F \times B_x^T}{Max\left(F \times F^T\ and\ F \times B_x^T\right)} \tag{22}$$

Sm values are calculated for each sample to determine the true category of samples in the fuzzy logic scale. Samples can be categorized as not satisfactory, satisfactory, good, very good, and excellent based on the highest S_m values obtained from each sample. It is concluded that any sample having the highest S_m values and their corresponding F value in standard fuzzy scale represents its true category in sensory ranking. Methodology of fuzzy logic was followed, as mentioned in the previous reports (Bhalerao et al., 2020; Dhar et al., 2021).

2.16. Statistical analysis

All the analyses were done in triplicates. The results were statistically correlated by ANOVA using a Tukey's multiple comparison test to identify differences at a level of significance at 95% confidence interval ($p < 0.05$) in SPSS (SPSS Inc., IBM, Version-16) software. Design-Expert software (StatEase®, DxT, Version 7.0) was used to analyze the data and optimize the HC process conditions. All figures were prepared using Origin 8.5 version.

3. Results and discussion

3.1. Effect of HC on pH, titratable acidity, and total soluble solids of tomato juice

From Table 1, pH, titratable acidity (%), and total soluble solids (°brix) of freshly squeezed tomato juice were 4.4, 0.26, 5, respectively. Based on the reported values (Tables 1 and S2) and the coefficients of the model, no differences in pH and titratable acidity between the control and HC processed samples were observed irrespective of treatment time and pressure applied. A similar observation was recorded when tomato juice was subjected to sonication where there was no significant difference ($p < 0.05$) in pH, °Brix, or titratable acidity even at maximum treatment conditions (61 μm for 10 min) irrespective of amplitude level and treatment time (Adekunte, Tiwari, Cullen, Scannell and O'Donnell, 2010). This might be because the effect of cavitation was not sufficient to increase H^+ concentration from the tomato juice, and the pH remained the same even at maximum treatment conditions (Raj et al., 2019). The values of TSS, pH, and titratable acidity of tomato juice at the highest treatment conditions of 15 psi at 30 min were 5.0 °Bx, 4.4, and 0.26%, respectively.

3.2. Effect of HC on the color parameter of tomato juice

As the treatment time proceeded, HC resulted in tomato juice with lower lightness, redness, and yellowness values (Table 1). The possible reason for this color change might be cavitation bringing out physical, chemical, and biological changes like the breakdown of sensitive components, i.e., enzymes and microorganisms, increase in diffusion rates, and reactions rate (Sala et al., 1995). Color degradation in tomato juice is governed by extreme pressure, and temperature levels (5000K and 500 MPa) obtained during cavitation. Moreover, the generation of free radicals such as hydroxyl radicals formed during cavitation oxidizes the carotenoid pigments, resulting in colorless compounds (Pinheiro et al., 2015).

The extent of color change was assessed based on total color differences in the present work. As observed from Table 1, the total color difference (ΔE*) values for cavitated tomato juice and raw juice were

Table 1
Physico-chemical properties of tomato juice processed with hydrodynamic cavitation at different time and pressures.

Pressure (Psi)	Time (min)	L*	a*	b*	ΔE*	pH	TA (%)	TSS (°Bx)
0	0	24.96 ± 0.06^{aA}	19.27 ± 0.57^{aA}	12.99 ± 12.99^{aA}	0^{Aa}	4.40 ± 0.01^{Aa}	0.260 ± 0.001^{aA}	5.00 ± 0.0^{Aa}
5	5	24.86 ± 0.01^{bB}	19.25 ± 0.01^{bB}	12.49 ± 0.06^{bB}	0.50 ± 0.06^{bB}	4.39 ± 0.01^{Aa}	0.260 ± 0.001^{aA}	4.98 ± 0.00^{aA}
	10	24.74 ± 0.03^{cB}	19.17 ± 0.03^{cB}	12.33 ± 0.04^{cB}	0.70 ± 0.03^{cB}	4.41 ± 0.01^{Aa}	0.259 ± 0.00^{aA}	4.98 ± 0.01^{aA}
	15	24.07 ± 0.03^{dB}	19.10 ± 0.05^{dB}	11.98 ± 0.09^{dB}	1.36 ± 0.05^{dB}	4.41 ± 0.01^{Aa}	0.261 ± 0.00^{aA}	5.00 ± 0.00^{aA}
	20	23.96 ± 0.03^{eB}	18.97 ± 0.02^{eB}	11.58 ± 0.06^{deB}	1.75 ± 0.04^{eB}	4.41 ± 0.01^{Aa}	0.261 ± 0.00^{aA}	4.98 ± 0.01^{aA}
	25	23.55 ± 0.01^{fB}	18.94 ± 0.06^{fB}	11.28 ± 0.06^{fB}	2.24 ± 0.05^{fB}	4.40 ± 0.01^{Aa}	0.260 ± 0.002^{aA}	5.00 ± 0.01^{aA}
	30	23.22 ± 0.03^{fB}	18.84 ± 0.08^{gB}	11.03 ± 0.08^{gB}	2.65 ± 0.04^{gB}	4.39 ± 0.01^{Aa}	0.259 ± 0.003^{aA}	4.99 ± 0.01^{aA}
7.5	5	23.96 ± 0.02^{bC}	19.22 ± 0.01^{bC}	12.51 ± 0.08^{bC}	1.11 ± 0.04^{bC}	4.39 ± 0.01^{Aa}	0.261 ± 0.001^{aA}	4.99 ± 0.00^{aA}
	10	23.86 ± 0.02^{cC}	19.20 ± 0.03^{cC}	11.88 ± 0.06^{cC}	1.57 ± 0.04^{cC}	4.40 ± 0.01^{Aa}	0.261 ± 0.002^{aA}	4.98 ± 0.01^{aA}
	15	23.52 ± 0.05^{dC}	19.07 ± 0.03^{dC}	11.54 ± 0.06^{dC}	2.05 ± 0.05^{dC}	4.40 ± 0.01^{Aa}	0.261 ± 0.002^{aA}	5.00 ± 0.00^{aA}
	20	23.46 ± 0.03^{eC}	18.97 ± 0.02^{eC}	10.96 ± 0.08^{deC}	2.54 ± 0.05^{eC}	4.40 ± 0.01^{Aa}	0.260 ± 0.002^{aA}	4.98 ± 0.01^{aA}
	25	23.16 ± 0.02^{fC}	18.87 ± 0.03^{fC}	10.91 ± 0.06^{fC}	2.77 ± 0.05^{fC}	4.40 ± 0.02^{Aa}	0.261 ± 0.002^{aA}	5.00 ± 0.00^{aA}
	30	22.94 ± 0.01^{fC}	18.73 ± 0.02^{gC}	10.24 ± 0.05^{gC}	3.45 ± 0.04^{gC}	4.41 ± 0.01^{Aa}	0.261 ± 0.002^{aA}	4.99 ± 0.01^{aA}
10	5	23.83 ± 0.07^{bD}	19.20 ± 0.02^{bD}	10.64 ± 0.09^{bD}	2.60 ± 0.07^{bD}	4.41 ± 0.00^{Aa}	0.261 ± 0.00^{aA}	4.98 ± 0.00^{aA}
	10	23.51 ± 0.05^{cD}	19.17 ± 0.01^{cD}	10.44 ± 0.10^{cD}	2.93 ± 0.07^{cD}	4.39 ± 0.01^{Aa}	0.261 ± 0.001^{aA}	4.98 ± 0.01^{aA}
	15	23.27 ± 0.17^{dD}	19.12 ± 0.02^{dD}	10.25 ± 0.08^{dD}	3.22 ± 0.15^{dD}	4.40 ± 0.01^{Aa}	0.260 ± 0.001^{aA}	4.98 ± 0.00^{aA}
	20	22.88 ± 0.10^{eD}	18.96 ± 0.01^{eD}	10.15 ± 0.09^{deD}	3.53 ± 0.13^{eD}	4.41 ± 0.00^{Aa}	0.259 ± 0.001^{aA}	4.98 ± 0.01^{aA}
	25	22.57 ± 0.11^{fD}	18.66 ± 0.03^{fD}	9.79 ± 0.07^{eD}	4.04 ± 0.12^{fD}	4.40 ± 0.01^{Aa}	0.261 ± 0.002^{aA}	5.00 ± 0.00^{aA}
	30	21.12 ± 0.11^{fD}	18.69 ± 0.02^{gD}	9.27 ± 0.15^{fD}	5.37 ± 0.18^{gD}	4.41 ± 0.00^{Aa}	0.261 ± 0.002^{aA}	4.99 ± 0.01^{aA}
12.5	5	23.27 ± 0.25^{bE}	19.17 ± 0.02^{bE}	9.76 ± 0.05^{bE}	3.65 ± 0.09^{bE}	4.39 ± 0.01^{Aa}	0.261 ± 0.001^{aA}	4.98 ± 0.00^{aA}
	10	23.07 ± 0.03^{cE}	19.11 ± 0.01^{cE}	9.72 ± 0.10^{cE}	3.78 ± 0.08^{cE}	4.39 ± 0.01^{Aa}	0.260 ± 0.002^{aA}	4.98 ± 0.01^{aA}
	15	22.16 ± 0.01^{dE}	19.05 ± 0.01^{dE}	9.26 ± 0.06^{dE}	4.66 ± 0.05^{dE}	4.39 ± 0.01^{Aa}	0.260 ± 0.004^{aA}	4.99 ± 0.00^{aA}
	20	21.31 ± 0.13^{eE}	18.90 ± 0.05^{eE}	9.12 ± 0.09^{deE}	5.33 ± 0.14^{eE}	4.39 ± 0.01^{Aa}	0.261 ± 0.001^{aA}	5.00 ± 0.00^{aA}
	25	21.07 ± 0.03^{fE}	18.77 ± 0.02^{fE}	8.84 ± 0.07^{eE}	5.70 ± 0.07^{fE}	4.39 ± 0.01^{Aa}	0.261 ± 0.002^{aA}	4.99 ± 0.01^{aA}
	30	20.96 ± 0.01^{fE}	18.64 ± 0.02^{gE}	8.33 ± 0.12^{fE}	6.17 ± 0.10^{gE}	4.39 ± 0.01^{Aa}	0.259 ± 0.001^{aA}	4.99 ± 0.01^{aA}
15	5	21.59 ± 0.06^{bF}	19.07 ± 0.03^{bF}	11.06 ± 0.04^{bF}	3.89 ± 0.09^{bF}	4.39 ± 0.01^{Aa}	0.259 ± 0.001^{aA}	4.98 ± 0.00^{aA}
	10	20.20 ± 0.09^{cF}	19.06 ± 0.02^{cF}	10.55 ± 0.04^{cF}	5.35 ± 0.07^{cF}	4.39 ± 0.01^{Aa}	0.259 ± 0.00^{aA}	4.98 ± 0.01^{aA}
	15	19.49 ± 0.05^{dF}	18.91 ± 0.03^{dF}	9.40 ± 0.03^{dF}	6.54 ± 0.05^{sF}	4.39 ± 0.01^{Aa}	0.261 ± 0.00^{aA}	4.99 ± 0.00^{aA}
	20	18.43 ± 0.09^{eF}	18.84 ± 0.02^{eF}	9.65 ± 0.78^{deF}	7.37 ± 0.36^{eF}	4.39 ± 0.01^{Aa}	0.261 ± 0.02^{aA}	4.98 ± 0.01^{aA}
	25	18.12 ± 0.08^{fF}	18.80 ± 0.05^{fF}	9.54 ± 0.04^{fF}	7.67 ± 0.06^{fF}	$4.39 \pm 0.01z^{a}$	0.281 ± 0.00^{aA}	4.98 ± 0.01^{aA}
	30	17.80 ± 0.12^{fF}	18.58 ± 0.06^{gF}	9.51 ± 0.09^{gF}	7.98 ± 0.09^{gF}	4.39 ± 0.01^{a}	0.259 ± 0.003^{aA}	4.99 ± 0.01^{aA}

Note: ΔE* represents total color change, TA represents titratable acidity, and sTSS represents total soluble solids. The values are denoted as mean ± standard deviation of three determinations. Values having different "a, b, c" alphabets in the superscripts are significantly different ($p < 0.05$) with respect to treatment time; Values having different "A, B, C" alphabets in the superscripts are significantly different ($p < 0.05$) with respect to cavitation pressure.

significantly different, and increased ΔE*values were noted with the increased treatment time and pressure. Consequently, maximum ΔE* (7.9) was observed for the juice treated at 15 psi for 30 min, and minimum ΔE* (1.25) was observed for the 5 psi for 5 min, respectively. Total color change values correlate with previous reports, which gives the range within which color change were not noticeable ($0 < \Delta E^* < 0.5$), slightly noticeable ($0.5 < \Delta E^* < 1.5$), noticeable ($1.5 < \Delta E^* < 3.0$), well visible ($3.0 < \Delta E^* < 6.0$), and greatly visible ($6.0 < \Delta E^* < 12.0$) (Cserhalmi et al., 2006). From this study, it can be concluded that samples HC treated using optimized conditions fall in the well visible category. HC treated samples were comparatively better in visual acceptability than thermally treated samples. Moreover, in the case of cavitated tomato juice, a decrease in L*, a*, b* values were observed. The negative linear interaction coefficients of models with R^2-value >0.94 from Table S2 and S3 also explain this trend, which might be due to the cavitation effect during processing.

3.3. Effect of HC on the viscosity of tomato juice

The viscosity of fresh tomato juice was 5.91 cP (Fig. 3a). On HC processing, both pressure and time had a synergistic influence ($p < 0.05$) on viscosity (Table S2). The decrease in viscosity might be due to the development of swirling cavitation during processing which brings strong shear force and intense cavitation as previously reported (Wang et al., 2015). Another reason for the decrement in viscosity was the rise in temperature during treatment conditions. Since, increase in temperature causes an increase in mobility of molecules, which is obvious and reflects the change in viscosity of the sample (Salehi et al., 2019). The decrease in viscosity values was noted maximum (5.0 cP) at the treatment conditions of 15 psi for 30 min and minimum (5.8 cP) at the treatment condition of 5 psi for 5 min (Fig. 3a), respectively. Optimized HC treatment (10 psi for 10 min) of tomato juice also showed a significant reduction ($p < 0.05$) in viscosity (5.6 cP) when compared to the unprocessed fresh juice sample. A similar observation was reported (Wang et al., 2015) while treating raw sugar syrup using HC, which resulted in a gradual decrease in intrinsic viscosity with an increase in downstream pressure due to the swirling effect. The reduced viscosity was attributed to the high cavitational energy that disturbed the solvation layer around hydrophilic colloids and reduced interactions between hydrophilic colloids and water molecules, resulting in more cohesion among colloidal particles sugar syrup. However, the thermal processing of tomato juice showed reduced viscosity at higher processing conditions. The possible reasons include the retention of soluble pectin and structural differences in cellular debris. The breakdown temperature is chosen for thermal processing also influences the viscosity of the tomato juice (Foda and McCollum, 1970). In summary, it can be said that cavitation pressure and treatment time had an antagonistic influence on the decrease in viscosity of the tomato juice sample.

3.4. Effect of HC on particle size reduction of tomato juice

Particle size distributions of HC tomato juice are summarized in Fig. 3b. Initial small particle size distribution due to HC, favors the homogenization process in tomato juice. In tomato juice processing, homogenization is an essential step that changes the actual juice structure, leading to less settlement and pulp separation from the continuous phase. Adding to that, homogenization provides improved bioavailability of active components present in the tomato juice. Homogenization additionally improves product quality and sensory acceptance. A significant reduction in particle size was observed for every treatment compared to the particle size of the control sample. In this study, maximum particle size reduction was observed at maximum treatment conditions of 15 psi for 30 min with 56% reduction in particle size compared to the control juice sample. Reduction in particle size during

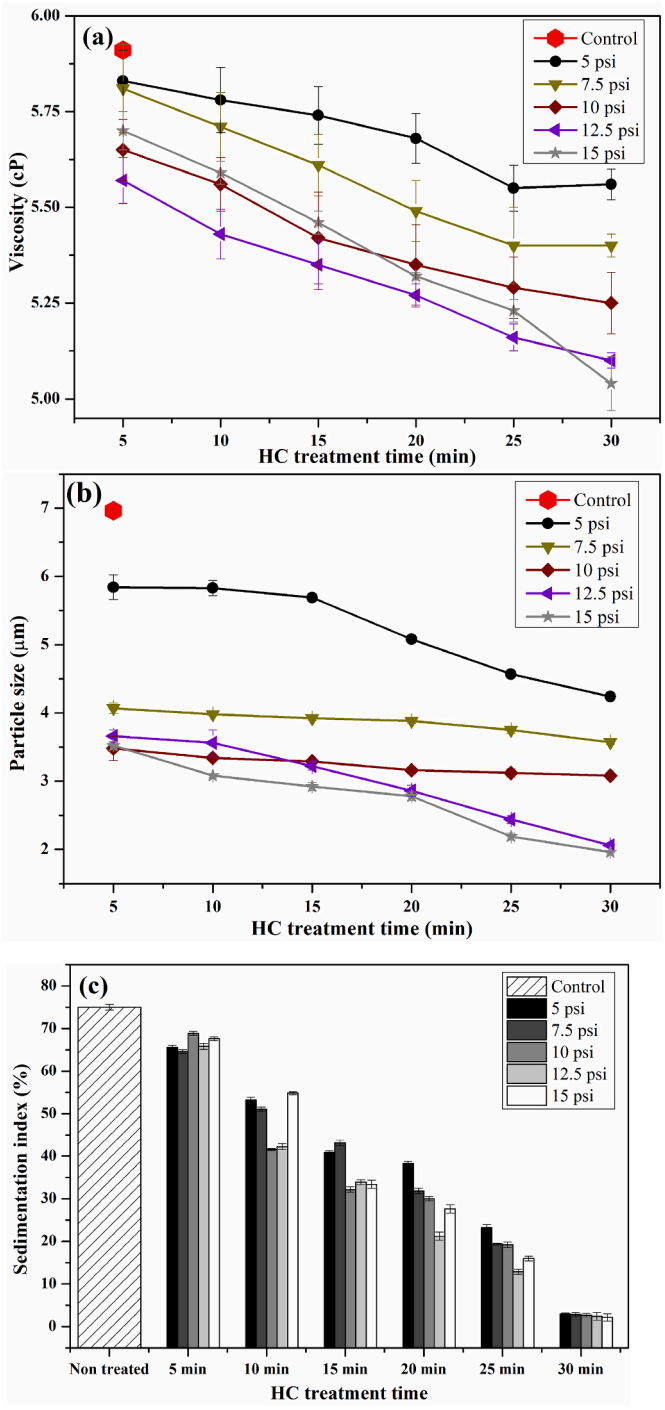

Fig. 3. Effect of hydrodynamic cavitation treatment at varying pressure and time conditions on (a) apparent viscosity (cP), (b) particle size (μm), and sedimentation index (%) of tomato juice.

HC is attributed due to strong turbulence, shock waves, and microjets generation during the violent collapse of microbubbles on processing (Serdula et al., 1996). The decrease in particle size was in accordance with what has been earlier seen in tomato juice processing treated at different pressure (Kubo et al., 2013). Heat treatment of tomato juice caused the breaking down of larger molecules resulting in a reduction in particle size. However, the particle size of HC optimized and thermally treated samples in the shelf-life study showed increasing effect due to the homogenization increases uniform particle size distribution. Therefore, HC processing induced a reduction in particle size, causing improved stability of tomato juice in fruit juice processing.

3.5. Effect of HC on sedimentation index of tomato juice

Tomato juice's sedimentation index (SI) was evaluated for both HC treated and control samples during 14 days of storage at 4 °C (Fig. 3c). Sedimentation of both treated and control samples was visually observed, as seen from Fig. 4. Control tomato juice showed higher separation of insoluble phase, and increased SI was noted as the storage time proceeded. At the end of 14 days of storage, the control sample exhibited 74% of SI at 4 °C. Higher sedimentation can be attributed to weaker inter-particle forces in large particles. Sedimentation follows the principle of Stokes law, where the sedimentation rate is directionally proportional to particle size and inversely proportional to the viscosity of dispersed medium (Kubo et al., 2013). Therefore, the reduction in particle size during HC processing helped improve the homogenized sample's stability. The settling rate decreased with the increase in cavitation treatment, and lesser sedimentation was observed at the end of 14 days of visual inspection (Fig. 3c). HC-treated samples showed greater stability, resulting in only 2% of SI at the end of the storage period. It was also observed that SI decreased with increased treatment time and pressure. Maximum and minimum SI values were 30.1% and 65.6% for cavitated tomato juice with treatment conditions of 15 psi, 30 min, and 5 psi, 5 min, respectively (Fig. 3c). The reason for improved stability can be attributed due to the reduction in particle size and the effect of homogenization in the HC-treated tomato juice (Terán Hilares et al., 2019).

Additionally, in the thermally treated samples (90 °C for 90 s) SI was 28% SI due to inactivation of pectin methyl esterases. These results are in accordance with the previously reported results of HPH processing by Kubo et al. (2013), who observed higher SI values for the control sample due to aggregation of large particles. In the present study, similar observations were noted (Figs. 3c and 4).

3.6. Effect of HC on lycopene of tomato juice

The total lycopene content in raw tomato juice was 39.3 mg/kg, according to previously reported values, i.e., 36–43 mg/kg (Terán Hilares et al., 2019). From Table 2, total lycopene content was more stable during HC than thermal treatment. No significant change in lycopene content was observed at all HC treatment conditions. No significant change in lycopene content was observed in both control and treated samples subjected to varying processing times and temperature (Terán Hilares et al., 2019). No lycopene degradation was reported in HC-treated fruit juices. However, lycopene degradation was observed in US-treated tomato juice, and the values reduced from 29.4 mg/kg to 15.2 mg/kg in 9min of ultrasound treatment. Thermal treatment of tomato juice (90 °C for 90 s) significantly reduced lycopene content from 39.3 to 25.6 mg/kg, similar to the observations of De Assis, Lima, & De Assis et al. (2001) under identical processing conditions (Table 2). Hence, overall HC processing improves physical attributes and does not affect bioactive compound content extensively.

3.7. Effect of HC on ascorbic acid of tomato juice

The ascorbic acid content of fresh, unprocessed tomato juice was 11.7 mg/100 mL. Similar results, i.e., 9.9–67.9 mg of ascorbic acid/100 mL, were reported by Sánchez-Moreno et al. (2006) in unprocessed tomato juice. Ascorbic acid reductions in the range of 2.4–32.7% were observed for every treatment time, and pressure combination probably due to oxidation reactions between ascorbic acid and free radicals (O^{-}, OH^{-}, HO_2^{-}) generated during HC processing. The ascorbic acid content at low (5 psi for 5 min) and high treatment (15 psi for 30 min) conditions were 1.9 and 5.8 mg/100 mL, and its corresponding percentage retention was 67.3% and 97.6%, respectively. It is evident from the results that the intensity of cavitation is high at higher treatment conditions,

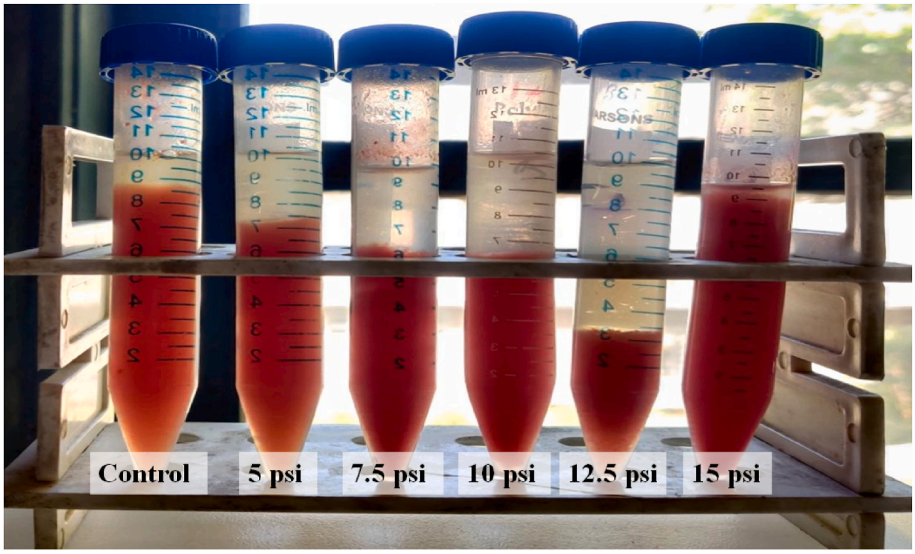

Fig. 4. Effect of different cavitation pressure (Control, 5, 7.5, 10, 12.5, and 15 psi) on sedimentation index in tomato juice treated for 30 min for 15 days at 4 °C.

causing a rapid reduction in ascorbic acid in HC-treated tomato juice, as seen in Table 2. In our study, ascorbic acid was relatively stable during HC processing than thermally treated tomato juice. These results align with the reports on pressure processing of tomato juice (Hsu et al., 2008). In summary, cavitated juice retained ascorbic acid better than thermally treated samples where the ascorbic acid content was only 7.2 mg/100 mL since ascorbic acid is liable to heat. The results suggest that HC could be used as a preservation technique and was noted to be better because of the lower temperature rise 48 °C even after 30 min of processing time.

3.8. Effect of HC on total phenolic compounds of tomato juice

Total phenolic compounds in freshly squeezed tomato juice were 47.8 mg GAE/100 mL, in accordance to previously reported results, i.e., 45 mg GAE/100 mL (Terán Hilares et al., 2019). From Table 2, the highest and lowest phenolic compound content (i.e., 46.6 and 39.0 mg GAE/100 mL) were obtained when processing the samples at 5 psi for 5 min and at 15 psi for 30 min, respectively. A significant ($p < 0.05$) reduction in the phenolic compound was observed at all HC treatment times and pressures. It was also noted that total phenolic compounds content was lower in the cavitated sample than the fresh, unprocessed tomato juice sample. The free radicals generated during HC processing lead to oxidative degradation of phenolic compounds. Similar observations were made by Pinheiro et al. (2015) in strawberry juice when subjected to ultrasound treatment. In summary, cavitated juice retained better total phenolic compounds than thermally treated sample where the total phenolic content was only 34.6 mg/100 mL since total phenolic content are labile to heat and a similar decrease in phenolic compounds were observed in thermally treated watermelon juice at 80 °C during 15 min respectively (Kaur et al., 2014).

3.9. Effect of HC on PME activity of tomato juice

The presence of pectin strongly influences the consistency of tomato juice. It is of utmost importance to control the breakdown of pectin and the inactivation of the enzyme responsible, i.e., pectic methylesterase (PME), for their degradation during processing. They de-esterify the pectin component and result in low methoxyl pectin, methanol, and free acids. De-methoxylated pectin forms cross-link with divalent cations (Ca^{2+}, Mg^{2+}), resulting in increased aggregation of molecules and precipitation of particles resulting in cloud destabilization and loss of turbidity of the tomato juice (Salas-Tovar et al., 2017). Therefore, suitable processing conditions are chosen to inactivate the quality deteriorating enzyme (PME) without affecting bioactive presence in the juice. In this study, PME activity of raw tomato juice came to be 2.6 meq. H^+ mL^{-1} min^{-1} where PME activity highly depends on the maturity of tomatoes procured for processing (Mason, 1997). Maximum PME inactivation was observed in 15 psi for 30 min (15% reduction) (Table 2). In this study, optimized HC processing (10 psi for 10 min) showed a 5% reduction in PME activity and considerably less PME activity than thermally treated tomato juice due to the low temperature employed in HC processing. HC efficacy in enzyme inactivation can be improved when coupled with thermal treatments.

PME inactivation in HC processing is achieved by mechanical means like bubble collapse, shock waves, and the generation of microjets damaging the integrity of PME in tomato juice. However, the inactivation was minimal due to cushioning effect in cavitation i.e., and increased vapor pressure can cause an ineffective collapse of microbubbles (Martynenko and Chen, 2016). It also agrees with ultrasound treatment, where not all enzymes are inactivated at mild temperature conditions (Makroo et al., 2017). It powerfully shows that HC processing with current processing conditions cannot achieve 100% PME inactivation in tomato juice.

The effect of HC on rate of PME inactivation was evaluated using a first-order kinetic model (Table 3). The high R^2 values (0.84–0.95) indicate the good fit model, and the D_{90} value was calculated from the corresponding k value of the model (Table 3, Fig. S2a). The time required for 90% reduction in PME activity requires two times less time in samples HC processed at 15 psi pressure than at 5 psi. Also, the rate constant K increases with additional cavitation in treatments performed at higher pressure and longer times. The time required to reduce PME activity to 50% ($t_{1/2}$) increases as the treatment levels increase.

3.10. Effect of HC on total plate count and its degradation kinetics in tomato juice

This study failed to achieve commercial log reduction (5 log reduction) for the pasteurization of fruit juices. However, the reduction in microbial load increased with an increase in treatment time and pressure (Table 4, Fig. S2b). The current study could achieve a maximum of about 1 log reduction when treated at maximum process parameter condition i.e., 15 psi and 30 min. In HC, the reduction in the microbial population is due to conditions of localized temperature and pressure during the collapse of microbubbles, thereby creating a shear force, turbulence, and generation of high energy (Katariya et al., 2020). Probably insufficient

Table 2
Effect of hydrodynamic cavitation processing on lycopene (mg/kg), ascorbic acid (mg/100 ml), total phenolic content (mg/100 ml), and PME activity (PMEU; meq H+ min-1 ml-1) of tomato juice treated at different times.

PRESSURE (PSI)	TIME (MIN)	LYCOPENE (MG/KG OF JUICE)	Ascorbic acid (MG/100 ML OF JUICE)	TPC (MG GAE/100 ML OF JUICE)	PMEU (MEQ H^+ MIN^{-1} ML^{-1})
0	0	39.25 ± 0.01^{aA}	11.71 ± 0.49^{aA}	47.82 ± 0.50^{aA}	2.57± 0.035^{aA}
5	5	39.24 ± 0.02^{aA}	11.43 ± 0.34^{aB}	46.57 ± 0.50^{bA}	2.54 ±0.036^{bA}
	10	39.23 ± 0.02^{aA}	11.23± 0.37^{bB}	46.02 ± 0.76^{cA}	2.48 ± 0.034^{cA}
	15	39.23 ± 0.03^{aA}	10.63± 0.27^{cB}	45.40 ± 1.00^{dA}	2.46 ± 0.036^{dA}
	20	39.22 ± 0.02^{aA}	10.29± 0.19^{deB}	44.80 ± 1.04^{eA}	2.36 ± 0.031^{eA}
	25	39.22 ± 0.01^{aA}	10.18 ± 0.76^{eB}	44.47 ± 1.81^{fA}	2.32 ± 0.029^{fA}
	30	39.23 ± 0.02^{aA}	9.91 ± 0.23^{eB}	44.22 ± 0.76^{fA}	2.30 ± 0.031^{gA}
7.5	5	39.24 ± 0.02^{aA}	11.54 ± 0.27^{aBC}	47.20 ± 0.50^{bB}	2.52 ± 0.033^{bB}
	10	39.23 ± 0.03^{aA}	10.97 ± 0.28^{bBC}	46.75 ± 0.29^{cB}	2.47 ± 0.0032^{cB}
	15	39.24 ± 0.02^{aA}	10.50 ± 0.37^{cBC}	46.39 ± 0.76^{cB}	2.39 ± 0.002^{dB}
	20	39.22 ± 0.02^{aA}	9.97± 0.43^{deBC}	45.69 ± 2.18^{dB}	2.32 ± 0.02^{dB}
	25	39.22 ± 0.02^{aA}	9.61 ± 0.36^{eBC}	44.43. ±1.04^{eB}	2.31 ± 0.09^{dB}
	30	39.21 ± 0.01^{aA}	9.47 ± 0.56^{eBC}	43.68 ± 1.00^{fB}	2.28 ± 0.03^{eB}
10	5	39.23 ± 0.02^{aA}	11.56 ± 0.22^{aC}	46.82± 0.50^{bC}	2.51 ± 0.03^{bC}
	10	39.23 ± 0.03^{aA}	11.0 ± 0.30^{bC}	46.19± 0.50^{bC}	2.45 ± 0.032^{cC}
	15	39.23 ± 0.03^{aA}	10.05 ± 0.54^{cC}	45.45± 0.29^{cC}	2.40 ± 0.02^{dC}
	20	39.22 ± 0.02^{aA}	9.65± 0.95^{deC}	44.05± 0.76^{dC}	2.33 ± 0.29^{eC}
	25	39.24 ± 0.02^{aA}	8.95 ± 0.27^{eC}	42.11 ± 1.04^{eC}	2.30 ± 0.029^{fC}
	30	39.23 ± 0.01^{aA}	8.55 ± 0.26^{eC}	41.66 ± 0.50^{fC}	2.25 ± 0.79^{gC}
12.5	5	39.24 ± 0.02^{aA}	11.25 ± 0.62^{aD}	47.10 ± 0.37^{bD}	2.52 ± 0.034^{bD}
	10	39.25 ± 0.02^{aA}	9.99 ± 0.19^{bD}	45.67 ± 0.05^{cD}	2.45 ± 0.032^{cD}
	15	39.24 ± 0.02^{aA}	9.21 ± 0.74^{cD}	44.47 ± 0.54^{dD}	2.41 ± 0.033^{dD}
	20	39.22 ± 0.01^{aA}	8.65 ± 0.06^{deD}	43.11 ± 0.34^{eD}	2.32 ± 0.37^{eD}
	25	39.23 ± 0.02^{aA}	8.37 ± 0.21^{eD}	40.86 ± 0.61^{fD}	2.28 ± 0.028^{fD}
	30	39.23 ± 0.01^{aA}	8.29 ± 0.20^{eD}	40.01 ± 0.62^{gD}	2.21 ± 0.07^{gD}
15	5	39.23 ± 0.01^{aA}	10.23 ± 0.17^{aD}	47.29 ± 0.14^{aE}	2.52 ± 0.063^{bE}
	10	39.23 ± 0.03^{aA}	9.57 ± 0.59^{bD}	44.23 ± 0.16^{bE}	2.48 ± 0.035^{cE}
	15	39.24 ± 0.02^{aA}	9.13 ± 0.05^{cD}	41.55 ± 0.22^{cE}	2.41 ± 0.037^{dE}
	20	39.23 ± 0.02^{aA}	8.20 ± 0.66^{deD}	40.76 ± 0.24^{dE}	2.26 ± 0.32^{eE}
	25	39.25 ± 0.01^{aA}	8.11 ± 0.63^{eD}	39.58 ± 0.34^{eE}	2.23 ± 0.09^{fE}
	30	39.23 ± 0.02^{aA}	8.00 ± 0.10^{eD}	39.01 ± 0.45^{eE}	2.17 ± 0.01^{gE}

Note: TPC: total phenolic content, and PMEU: pectin methyl esterase units per unit volume juice (meq H^+ ml^{-1} min^{-1}). The values are denoted as mean ± standard deviation of three determinations. Values having different "a, b, c" alphabets in the superscripts are significantly different ($p < 0.05$) with respect to treatment time; Values having different "A, B, C" alphabets in the superscripts are significantly different ($p < 0.05$) with respect to cavitation pressure.

Table 3
Effect of different combinations of cavitation pressure-treatment time on PME enzyme inactivation rate constant (k min-1), t1/2 (min), and D (min) in tomato juice.

PRESSURE (PSI)	RATE CONSTANT (K X 10^{-3} MIN^{-1})	D_{90} (MIN)	$T_{1/2}$ (MIN)	R^2
5	4.2 ± 0.01^{a}	581.0 ± 0.32^{a}	193.9 ± 0.25^{a}	0.87
7.5	4.8 ± 0.04^{b}	545.8 ± 0.53^{b}	182.3 ± 0.22^{a}	0.94
10	5.3 ± 0.05^{c}	426.6 ± 0.22^{c}	142.5 ± 0.26^{a}	0.84
12.5	7.2 ± 0.02^{d}	309.8 ± 0.65^{d}	103.6 ± 0.25^{a}	0.95
15	9.3 ± 0.01^{e}	269.0 ± 0.54^{e}	90.0 ± 0.18^{a}	0.95

Note: The values are denoted as mean ± standard deviation with three determinations. Values having different "a, b, c" alphabets in the superscripts are significantly different ($p < 0.05$) with respect to pressure.

Table 4
Effect of different combinations of cavitation pressure-treatment time on total plate count in tomato juice.

Conditions	Microbial log Reduction	
	15 min HC treatment min	30 min HC treatment min
5 psi	0.22	0.34
7.5 psi	0.31	0.46
10 psi	0.34	0.59
12.5 psi	0.46	0.78
15 psi	0.72	0.94
HTST 90 °C for 90 Sec	4.95	

HC effect responsible for low inactivation of microbial counts and the minimum rise in temperature at maximum treatment condition of 15 psi at 30 min was 48 °C respectively. This microbial inactivation can be improved by increasing intensity, number of pass and thermal assistance in HC processing (Arya et al., 2021). Although, thermally treated juice showed 4.9 log reduction in total plate count (Table 4). HC can only retain the bioactive compounds with minimal reduction in the microbial count. Efficacy of HC treatment for microbial inactivation can be attained when coupled with other non-thermal technology. Microbial reduction in tomato juice treated with HC was characterized using a log-linear model (Table 5). From Table 4, it can be observed that as the cavitation pressure increases, the microbial degradation rate increases. The time required for a one log cycle reduction in the microbial population can be achieved approximately two times less time at pressure 15 psi than 5 psi.

Table 5
Effect of different combinations of cavitation pressure-treatment time on microbial inactivation rate constant (k min-1), t1/2 (min), and D (min) in tomato juice.

PRESSURE (PSI)	RATE CONSTANT (K X10^{-3} MIN^{-1})	D_{90} (MIN)	$T_{1/2}$ (MIN)	R^2
5	26.73 ± 0.01^{a}	86.17 ± 0.83^{a}	25.93	0.98
7.5	35.23 ± 0.02^{b}	65.36 ± 0.21^{b}	19.67	0.97
10	45.30 ± 0.01^{c}	50.83 ± 0.11^{c}	15.30	0.99
12.5	59.80 ± 0.03^{d}	38.51 ± 0.01^{d}	11.59	0.99
15	72.33 ± 0.01^{e}	31.83 ± 0.02^{e}	9.58	0.92

Note: The values are denoted as mean ± standard deviation of three determinations. Values having different "a, b, c" alphabets in the superscripts are significantly different ($p < 0.05$) with respect to pressure.

Table 6
Overall Ranking in comparison with all 10 min treated sample at different pressure are compiled below.

TREATMENT	SAMPLE	OS	CATEGORY	RANKING
CONTROL	S1	0.76	Very good	1
5 PSI 10 MINS	S2	0.65	Satisfactory	5
7.5 PSI 10 MINS	S3	0.67	Satisfactory	4
10 PSI 10 MINS	S4	0.71	Very good	2
12.5 PSI 10 MINS	S5	0.63	Satisfactory	6
15 PSI 10 MINS	S6	0.73	Good	3
HEAT TREATED (90 °C FOR 90 SEC)	S7	0.59	Satisfactory	7

3.11. Optimized conditions and model validation

The coefficients of terms significant at $p < 0.05$ in the imperial models indicating the effect of HC processing parameters on each parameters are depicted in Table S2. The multivariable numeric optimization was performed based on the response generated during processing and by assigning goals for each response. High importance was given to bioactive compounds and enzyme inactivation for prolonging the shelf life of treated tomato juice and also with the aim of retaining bioactive compounds present in tomato juice. Bioactives including lycopene, ascorbic acid, total polyphenol compounds, redness, and PME inactivation, were also maximized. From Table 7, it was observed that both estimated and experimental values had less than 2% difference signifying that the obtained optimized conditions are highly acceptable with the best overall desirability of 0.71 (Table 7, Fig. S3). Hence, the optimized condition for HC-treated tomato juice was 10 psi cavitation pressure for 10 min of treatment time.

3.12. Sensory evaluation using fuzzy logic for optimized conditions

Color, freshness flavor, and mouthfeel are the most important quality characteristic of tomato juice. From Table 6 the results of the sensory analysis showed that sample S1 (control), S6 (15 psi for 10 min), S4 (10 psi for 10 min) exhibited top sensory score and fared better when compared to other HC treated and heat-treated samples. The sample processed at the optimized conditions displayed better acceptance than the heat-treated sample. At higher HC treatment conditions, sensory quality was lost due to the occurrence of free radicals, oxidation of flavoring compounds, and difference in sugar to acid ratio, respectively (Abid et al., 2013). In short, panelists preferred HC samples compared to heat-treated samples in terms of sensory score and retention of bioactive compounds in tomato juice.

3.13. Shelf-life evaluation

The shelf life of HC and thermally treated tomato juice did not significantly change in TSS, pH, and titratable acidity (Table 8) during the storage at 4 °C for 15 days. The results correlate with the previous report where the effect of high-pressure processing of apple juice did show a significant difference in physicochemical properties during treatment and storage (Señorans et al., 2003). The shelf-life of the samples that had been thermally treated or processed with HC at optimized conditions showed a decrease in TCD values upon 15 days of storage. A similar observation was reported in (Pinheiro et al., 2015), where lower a* values were observed for US-treated tomato juice during storage conditions of 8 days at 10 °C. During storage, the separation of insoluble particles was higher due to the aggregation of particles. Hence both sedimentation index and particle size of treated sample increased with an increase in storage time. A decrease in viscosity was observed during storage due to presence of residual PME activity. A similar observation was seen in the pressure processing of tomato juice (Gardner et al., 2000). Bioactive compounds, including lycopene, ascorbic acid, and phenolic compounds, decreased in both HC treated and thermally treated tomato juice. The residual oxygen in the stored sample resulted in ascorbic acid and lycopene content degradation during the shelf-life study (Jabari et al., 2018). The possible reason for the decrease in phenolic content during storage was attributed to hydroxyl radicals generated during cavitation and gases like O_2 and N_2, which diffuse into PET bottles during storage, promoting the oxidative degradation of phenolic compounds. There was a slight increase in PME activity during storage as residual PME caused the increase in PME activity in both HC and thermally treated tomato juice. Expanded PME action may directly result from increased pectin content during storage because of the change of insoluble proto-pectin into dissolvable pectin formed during storage (Kaur et al., 2014). By considering the result as a whole, the shelf life of HC-treated tomato juice had better quality attributes and retention of nutrients when compared to thermally treated tomato juice after storage at 4 °C for 15 days, respectively.

4. Conclusion

A full factorial design was utilized to decide the optimum working conditions of HC processing to acquire the best quality of tomato juice. The optimized condition of HC processing was found to be 10 psi for 10 min. There was no significant change in HC treated tomato juice in terms of the quality attribute. HC treatment had a significant effect on tomato juice's sedimentation index, viscosity, and particle size. The detrimental effect of HC processing on bioactive constituents was minimal when compared to the thermal treatment. When combined with other hybrid non-thermal treatments like ultrasound pulsed electric and thermal assistance, HC treatment can result in more significant inactivation of quality deteriorating enzymes and microorganisms in tomato juice. HC treatment can be an alternative technology for homogenizers when scaled up in the industrial level.

Table 7
Experimental and predicted responses for physicochemical attributes, PME enzyme inactivation and nutritional content of optimized experimental trial.

PARAMETER/RESPONSE	GOAL	CONSTRAINTS (L_L-U_L)	IMPORTANCE	PREDICTED VALUE	EXPERIMENTAL VALUE
PRESSURE (PSI)	In range	5–15	3	9.86 Desirability: 0.71	10
TIME (MINS)	In range	5–30	3	9.83	10
A*	Maximize	18.58–19.25	4	19.18	19.17
ΔE	Maximize	0.50–7.98	4	2.81	2.93
LYCOPENE (MG/KG)	Maximize	39.01–39.24	4	39.20	39.23
TPC (MG GAE/100 ML)	Maximize	39.17–47.33	4	46.52	46.19
Ascorbic acid (MG AA/100 ML)	Maximize	7.88–11.57	4	11.28	11.00
SEDIMENTATION INDEX (%)	Minimize	30.13–66.82	4	40.37	41.52
VISCOSITY (CP)	Maximize	5.03–5.82	3	5.69	5.56
PARTICLE SIZE (MM)	Minimize	1.95–5.83	3	3.64	3.34
PME ENZYME INACTIVATION (%)	Maximize	2.17–2.54	5	2.48	2.46

Note: ΔE is total color change, TPC is total phenolic content, and PME is pectin methyl esterase activity, L_L is lower limit, and U_L is upper limit.

Table 8
Effect of storage (15 days at 4 °C) on physicochemical (PH, TA, TSS, viscosity (Cp), L*, a*, b*, ΔE, and sedimentation index (%)) and bioactives (lycopene (mg/kg), vitamin C (mg/100 ml), total phenolic content (mg/100 ml), and PME activity (PMEU; meq H+ min-1 ml-1)).

PARAMETERS	0-DAY STORAGE			SHELF LIFE (15 DAYS AT 4 °C)		
	Control	HC (10 psi for 10 min)	Heat treated (90 °C for 90 s)	Control	HC (10 psi for 10 min)	Heat treated (90 °C for 90 s)
PH	4.40±0.01^{a}	4.39±0.01^{a}	4.39±0.00^{a}	4.40±0.01^{a}	4.40±0.01^{a}	4.39±0.01^{a}
TA	0.26±0.01^{a}	0.26±0.01^{a}	0.26±0.01^{a}	0.29±0.01^{b}	0.26±0.01^{a}	0.26±0.01^{a}
TSS	5.00±0.00^{a}	4.97±0.01^{b}	4.98±0.01^{a}	4.5±0.00^{b}	4.97±0.01^{a}	4.97±0.01^{a}
VISCOSITY (CP)	5.90±0.17^{a}	5.56±0.02^{b}	4.91±0.05^{c}	5.90±0.15^{a}	5.45±0.02^{b}	4.90±0.02^{c}
L*	24.96±0.05^{a}	23.51±0.05^{a}	19.45±0.10^{b}	22.96±0.05^{a}	19.25±0.01^{b}	14.25±0.04^{c}
A*	19.27±0.57^{a}	19.18±0.26^{a}	5.66±0.15^{b}	8.02±0.57^{a}	5.25±0.01^{b}	2.31±0.06^{c}
B*	12.99±0.01^{a}	10.44±0.10^{b}	9.56±0.10^{b}	10.95±0.01^{b}	9.86±0.02^{b}	16.24±0.04^{a}
ΔE	0±0^{c}	2.81±0.23^{b}	15.08±0.11^{a}	8.89±0^{b}	7.18±0.00^{b}	21.50±0.04^{a}
SI (%)	74.99±0.68^{a}	40.52±1.22^{b}	28.25±0.23^{a}	79.95±0.68^{a}	41.52±0.22^{b}	29.23±0.60^{c}
TPC (MG GAE/100 ML)	47.91±0.58^{a}	46.19±0.89^{a}	34.64±0.76^{b}	48.55±0.58^{a}	41.19±0.15^{b}	30.41±0.10^{c}
LYCOPENE (MG/KG OF TOMATO JUICE)	39.25±0.01^{a}	39.23±0.39^{a}	25.64±0.01^{b}	37.62±0.01^{a}	38.22±0.10^{a}	22.21±0.02^{b}
ASCORBIC ACID (MG/100 ML)	11.71±0.49^{a}	11.00±0.53^{a}	7.19±0.16^{b}	10.81±0.49^{a}	10.01±0.05^{a}	6.13±0.02^{b}
PMEU (MEQ. $H^{+}ML^{-1}$ MIN^{-1})	2.57±0.10^{a}	2.46±0.31^{a}	0.21±0.01^{b}	2.59±0.10^{a}	2.50±0.01^{a}	0.22±0.02^{b}
REDUCTION OF PME ACTIVITY (%)	0		92.21	0	2.72	91.43

Note: TA is titratable acidity, TSS is total soluble solids, ΔE is total color change, SI is sedimentation index, TPC is total phenolic content, and PMEU is pectin methyl esterase units. All values are in mean ± standard deviation of (n = 3) three determinations, different letters used in the same rows at 0 day and 15 day as superscripts indicate significant differences ($p<0.05$) between the means.

CRediT authorship contribution statement

G. Vigneshwaran: Formal analysis, Investigation, Writing – original draft. **Pavankumar Ramdas More:** Writing – review & editing. **Shalini Subhash Arya:** Conceptulization, Writing – review & editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no direct or indirect known competing financial interests or personal relationships that could have appeared to influence the subject matter discussed and reported in this paper.

Acknowledgement

The authors thank All India Council for Technical Education (AICTE), New Delhi for the financial support in carrying out the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crfs.2022.01.025.

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