Arya *et al.*
*Food Production, Processing and Nutrition* (2023) 5:36
https://doi.org/10.1186/s43014-023-00149-w

Food Production, Processing and Nutrition

**REVIEW** **Open Access**

# Recent progress and future perspectives on non-thermal apple juice processing techniques

Shalini S. Arya[1*], Nachal Nachiappan[1], Roji Waghmare[2] and Mohmad Sayeed Bhat[1]

## Abstract

Fresh apple juice is one of the most popular and consumed juice, owing to its pleasant taste, natural flavour and nutritional richness. Regular consumption of apple juice is associated with reducing the risk of cancer, cardiovascular related diseases, asthma and diabetes. However, the shelf life of apple juice is limited by detrimental effect of enzymes. Due to the demand of wholesome nutritious product, there arises a need for adoption of novel non-thermal techniques as they help to retain the nutritional content and at the same time aid in improving the shelf life as compared to the thermal treatment.

High pressure processing (HPP), pulsed electric field (PEF), ultrasound, pulsed light, UV, high-pressure homogenization (HPH) and hydrodynamic cavitation (HC) are all examples of novel procedures tested and tried for the better retention of nutritional and phytochemical composition in apple juice. This study aimed to find the influence of these mechanisms on the quality and composition of apple juice.

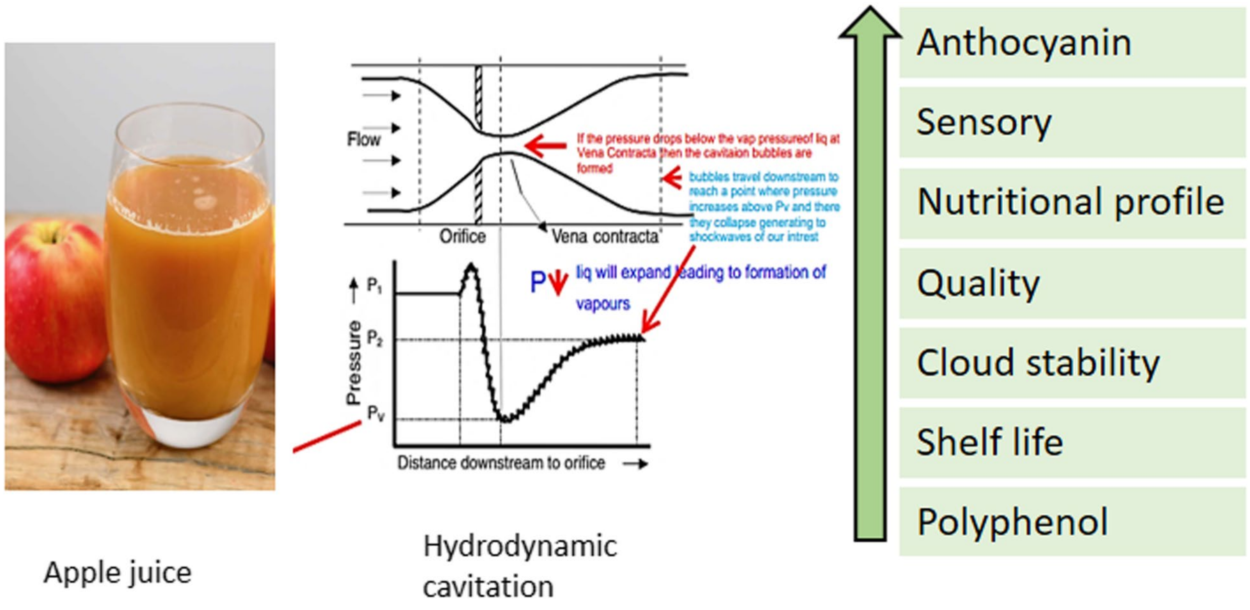
Apple juice processing has been successfully examined using non-thermal techniques. These exhibited promising results in terms of minimising physical, chemical, enzymatic and microbial deterioration of the apple juice while still retaining a high percentage of nutritious components. Though all the non-thermal process require a hurdle approach for inactivation of enzymes, HC can be a better alternative in terms of operating costs and ease in handling the bulk volumes of juice.

**Keywords** Bioactive, *Malus domestica*, Non-thermal, Nutritional, Phytochemical

---

*Correspondence:
Shalini S. Arya
shalu.ghodke@gmail.com; ss.arya@ictmumbai.edu.in
Full list of author information is available at the end of the article

## Graphical Abstract



## Introduction

Apples (*Malus domestica*) are one of the most commonly consumed and widely appreciated fruit due to its nutritional benefits. Some of the common varieties of apple are Classic red, Honey crisp apple, Gala, Granny smith, McIntosh golden and Red delicious. Red delicious a red bright apple renowned for crunchy texture and mildly sweet flavour. Gala is a crisp and has an aromatically sweet feature. Fuji apples are super sweet and flavourful apple. Granny smith apples are known for its delicious tart flavour and crunchy. Due to its convenience and ability to be processed into fruit juice, their consumption has been shifted towards fruit juice. Apple juice is the second most widely consumed fruit juice and popular among all age groups owing to its native taste. Apple juice is considered as a functional food due to its health promoting benefits apart from its nutritional content (Rupasinghe & Yu 2012). Nutritional content of apple juice is influenced by many spheres of factors which include type of cultivar, maturity, climate and processing methodology to extract juice. Processing methodology to extract juice plays a vital role in nutritional composition of yield juice. For instance, the loss in the vitamin C content in the clear apple juice is more, than cloudy apple juice because the former requires double pasteurisation treatment as compared to the single pasteurisation treatment of the later (Massini et al. 2018). The famous phrase "an apple a day keeps a doctor away" refers to the special health benefits offered by the phytochemical composition of apple juice (polyphenols and antioxidants). Fresh matured apples are chosen for production of fruit juices, where large amount of starch content would have been converted into sugars. The most common sugars present in the apple juice include fructose, glucose and sucrose.

Protein content and amino acid composition of apple juice is significantly low with aspartic and glutamic acid being the most predominantly present amino acids presenting in the juice. Among micronutrients only vitamin C content is higher and in minerals potassium, phosphorous and calcium are the most prevalent in apple juice (Lee 2012). Table 1 summarizes the compositional and nutritional characteristics of apple juices (per 100 g) (adopted from the USDA manual 2014). The nutraceuticals benefit of apple juices are mainly because of rich phytochemical composition which includes total phenolics and antioxidant activity.

## Bioactive constituents of apple and proven health benefits

Apples are rich source of phytochemicals which include phenolics, antioxidants and flavonoids. There are five major phenolic groups present in apple juice which includes flavonols, flavanols, anthocyanins, hydroxycinnamic acids, and dihydrochalcones, with hydroxycinnamic acids and flavonoids being the major contributors. The

**Table 1** Compositional and nutritional characteristics of apple and apple juice

| Nutrient | Unit | Apple (≈ 100 g) | Apple juice (100 ml) |
|---|---|---|---|
| Water | g | 83 | 88.24 |
| Energy | Kcal | 62.38 | 46 |
| Protein | g | 0.29 | 0.10 |
| Lipid (Fat) | g | 0.64 | 0.13 |
| Carbohydrate | g | 13.11 | 11.30 |
| Total sugars | g | 11.12 | 9.62 |
| Total dietary fibre | g | 2.59 | 0.2 |
| Calcium | mg | 13.68 | 8 |
| Iron | mg | 0.26 | 0.12 |
| Magnesium | mg | 8.09 | 5 |
| Phosphorous | mg | 10.44 | 7 |
| Sodium | mg | 1.43 | 101 |
| Potassium | mg | 116 | 4 |
| Zinc | mg | 0.09 | 0.02 |
| Folate (DFE) | µg | 3.04 | 0 |
| Niacin | mg | 0.25 | 0.073 |
| Riboflavin | mg | 0.01 | 0.017 |
| Thiamin | mg | 0.03 | 0.021 |
| Vitamin A | µg | 0 | 0 |
| Vitamin $B_6$ | mg | 0.04 | 0.018 |
| Vitamin C | mg | 3.57 | 0.9 |
| Vitamin E | mg | 0.02 | 0.01 |

Source: Apple Composition from Indian Food Composition Table, NIN, 2017. Apple Juice Composition Adapted from the USDA National Nutrient Database for Standard Reference, Release 27, 2014

recent studies have reported the bioactive constituents present in different apple varieties are flavan-3-ols (polymeric procyanidins), flavan-3-ols (monomers), dihydrochalcones, phenolic acid, flavanols and anthocyanins in the range of 455.2–1325, 145.8–248.8, 10.9–12, 36.3–1117, 34–44.6, 0.9–1.9 mg/100 g (dw), respectively (Wojdyło et al. 2021) (Table 2).

Antioxidant activity of apple juice is largely provided by vitamin- C and polyphenol content apart from carotenoids and vitamin E, with polyphenols being the major contributor of around 80% of the antioxidant activity and vitamin C around 5% (Gliszczynska-Swiglo & Tyrakowska 2003). Only a fraction of phenolic compounds is found in free form and major fractions are bound to cell wall in plant tissues. Among all the other fruits, apples have the highest proportion of free phenolics and bound phenolics are less bioavailable since they need to release from food matrix during digestion. 22% of polyphenol content in diet is met by apple consumption. Flavonoids also contribute significantly to antioxidant activity because of their ability to lower the redox potential and donate electron and hydrogen atoms. Procyanidin content of apple juice is also related to their high antioxidant activity. Phenolic compounds in apple juice are influenced by many factors which include cultivar variety, location and maturity (Starowicz et al. 2020). Processing has an impact on phytochemical composition of apple juice and major losses occur during extraction of apple juice. Major changes occur in phenolic composition during pressing and crushing as there is greater interaction between polyphenols, polyphenol oxidase enzyme (PPO) and cell wall matrix resulting in conversion to o-quinones (Renard et al. 2011). Cloudy apple juice has higher phenolic content (462.2 ± 30.7 mg/L) than clear juice (160.4 ± 35.9 mg/L) (Markowski et al. 2015). Polyphenols are sensitive to enzymatic and non-enzymatic hydrolysis which occur during enzyme pulping and storage respectively. Membrane filtration carried out during extraction of fruit juice has significant effect on phenolic composition. The loss of phenolic content during processing of fruit juice is reflected in reduction of antioxidant content also. Regardless of the method of processing, most of the total phenolics are retained in the pomace of apple juice, especially proanthocyanidins for their stronger binding effect with cell wall and hence justifies the low anthocyanin content in the apple juice (Starowicz et al. 2020).

Apple juices are known to provide many health benefits and regular consumption of apple juice is associated with the reducing the risk of cancer, cardiovascular related diseases, asthma and diabetes. Polyphenols in apples provide ample amount of health benefits which include effect on aging and other common health issues. The recent studies on the potentials of apple bioactive constituents for chronic disease prevention have reviewed the role of apples as potential antioxidants, immune system modulators, protection of gastro-intestinal tract (GIT), protection of type 2 diabetes, cancer and prevention of cardiovascular diseases as well (Oyenihi et al. 2022).

## Methods for processing of apple juice for extension in shelf life

Recent trends highlight the nutritional quality as the prime factor for acceptability of a product among consumers. Deteriorative changes in apple juice can be brought under control by inactivating PPO enzyme and microbial content employing different techniques like heating, freezing, lowering the pH, addition of preservatives and non-thermal treatments.

### Thermal processing of apple juice

Traditionally and since long time thermal treatments have been adopted to improve the shelf-life stability of fruit juices. Within thermal treatment different time-temperature domain has been employed suiting the need

**Table 2** Bioactive constituents of apple fruit *(adapted from* Wojdyło et al. 2021*)*

| Fruit | Cultivar | Flavan-3-ols | | Dihydro-chalcones | Phenolic acid | Flavonols | Antho-cyanins | Antioxidant capacity (mmol Trolox/100 g dw) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | PP | Monomers | | | | | ABTS | FRAP | ORAC |
| **Apple** | Szampion | 1325.0 ± 25.3 | 248.8 ± 9.5 | 12.0 ± 1.4 | 1117.1 ± 32.1 | 44.6 ± 4.6 | 1.9 ± 0.2 | 20.5 ± 1.2 | 16.6 ± 0.3 | 61.2 ± 1.3 |
| | Florina | 705.1 ± 12.6 | 261.9 ± 6.3 | 10.9 ± 1.1 | 60.1 ± 24.5 | 43.3 ± 2.4 | 0.9 ± 0.1 | 18.3 ± 1.0 | 17.9 ± 0.6 | 41.1 ± 1.4 |
| | Empire | 455.2 ± 11.2 | 145.8 ± 8.5 | 11.5 ± 1.1 | 36.3 ± 25.9 | 34.0 ± 3.6 | 0.9 ± 0.2 | 15.4 ± 0.5 | 13.8 ± 0.9 | 23.2 ± 1.1 |

of product. Low temperature long time (LTLT) and high temperature short time (HTST) treatments are the most common methodology adopted for pasteurization of fruit juices. Standard juice pasteurization, according to FDA must achieve 5 log reduction and accordingly different time- temperature combinations are set to ensure this decrease (U.S. Food and Drug Administration 2001).

Under LTLT process, apple juices are treated thermally at 63–65 °C for 20–25 min and this process is now mostly replaced with HTST process due to undesirable quality changes of the fruit juices. HTST is favoured over LTLT process since it involves less duration of heat treatment. Moyer and Aitken (1980), carried out pasteurization at 90 °C for 30 s, whereas Riener et al. (2008), carried out pasteurization of apple juice using tubular heat exchanger at 72 °C for 26 s. Charles-Rodríguez et al. (2007), carried out thermal treatment of apple juice at 73, 80 and 83 °C at a holding time of 27 s to compare its effect with pulsed electric field (PEF) in terms of pasteurization effect. Krapfenbauer et al. (2006), studied the effect of thermal treatment on the quality of apple juice by varying the temperature domain between 60 and 90 °C and short time of 20–100 s. The study highlighted the fact that around 80 °C PPO was completely inactivated and best stability of cloud and colour retention was achieved by HTST treatment between 70 °C/100 s and 80 °C/20 s. Thermal pasteurization treatments (LTLT & HTST) help in elimination of endogenous enzymes like PPO and POD and achieve standard log reduction but they also impair the quality of apple juice. Apple juices treated thermally are nutritionally depleted and bioactives in them are degraded because of their heat liable nature. They also lose the market share as people nowadays prefer fresh like nature and taste, which is better retained using non thermal treatments. Non thermal treatments have captured the current market trends as they preserve fresh like nature, retain bioactives and also help in extending the shelf life of fresh juice by eliminating deteriorative enzyme content and microbial population.

## Non-thermal processing of apple juice

Need for natural, nutritionally rich and convenient food is fast growing among consumers these days and lead to the development of the innovative technologies for preservation of fruit juices. It includes various technologies like High Pressure Processing (HPP), Pulsed Electric Field (PEF), Ultrasound, Pulsed light, UV, and High-Pressure Homogenization and Hydrodynamic cavitation. Non thermal processing of fruit juice involves treating the fruit juice at lower temperature ranges usually below 40 °C and each non thermal technique involves different principles and techniques for the preservation of the fruit juices.

### *HPP*

High Hydrostatic Pressure Processing (HPP) is a novel alternative method to thermal treatment in terms of its ability to inactivate enzymes and reduce microbial content at a lower temperature range. The magnitude of the temperature change depends on the thermal properties & compressibility of the substance along with its initial temperature & target pressure. In this process fruits juices are subjected to elevated pressure domain with or without temperature assistance. This helps in the retention of fresh like nature and bioactive constituents of juices due to lower processing temperatures. HPP is governed by isotactic and Le Chatelier principle and mainly applicable to fluids. Initial investment of this technology is quite high but is economical in the long run as it utilizes electrical energy only and is green. This novel methodology has now been extended to all fluid foods and their effect on rheological properties, inactivation kinetics of enzymes and microbial population, bioactives and quality of fluids have been studied (Gupta & Balasubramaniam 2012). Needs et al. (2000) evaluated the effects of HPP on casein micelle structure and enzyme coagulation. High-pressure treatments of milk up to 600 MPa results in denser network in rennet catalyzed formation of gels than gels produced using non pressure-treated milk. At pressures over 400 MPa, the higher storage modulus and casein micelles were found to be completely disrupted and syneresis from pressure treated gels is lower at pressures below 400 MPa. Buckow et al. (2009), studied about inactivation kinetics of PPO enzyme in apple juice under different pressure and temperature domains (0.1–700 MPa and 20–80 °C). Their work revealed the fact that pressure and temperature had a synergistic effect on PPO inactivation above 300 Mpa and antagonist effect at lower pressure domains. The work of Abid, Jabbar, Hu, Hashim, Wu, Lei, and Zeng (2014), also highlighted the ability of HPP combined with ultrasound to inactivate enzymes and microbial load in apple juice. The literature support the fact that HPP can improve the shelf-life stability of fruit juices by retaining fresh like nature and nutritional content and comes out to be a potential use in hurdle technology.

### *PEF*

Pulsed Electric Field (PEF) is another novel alternative to the thermal processing which helps in inactivating spoilage enzymes and microbiota with minimal impact on quality and nutritional content. It is addressed more towards liquid foods and restricted to fluids which can withstand high electric fields, have low electrical conductivity and do not form bubbles. This methodology involves application of high voltage electricity at regular intervals in a pulse mode. The high voltage electricity is the range of 20–80 kV for microseconds (Rupasinghe & Yu 2012). Sanchez-Vega et al. (2009), established the fact that PEF treatment at 38.5 kV/cm$^3$ and 300 pulses/sec at 50 °C inactivated around 70% PPO in apple juice and retained better physiochemical and bioactive properties compared to ultra-high pasteurization treatment where original sensorial and nutritional characters are affected. PEF can be proposed as an alternative method for pasteurization at lower temperatures. Heinz et al. (2003), studied the impact of temperature on lethality and energy efficiency of apple juice pasteurization by PEF treatment and concluded that by increasing the temperature from 55 to 65 °C energy requirement can be brought down to 40 kJ/Kg from 100 and at the same time 6 log reduction of *E. coli* strain can be achieved. Work of Riener et al. (2008), revealed that around 70% of PPO and POD can be inactivated in apple juice using combination of preheating to 50 °C and PEF treatment for 100 µs at 40 kV/cm$^3$ and this method of treatment yielded higher inactivation compared to conventional mild thermal pasteurization. PEF treatment has yielded promising results in extending the shelf life by having minimal impact on sensorial and nutritional profile.

### *Ultrasound*

Ultrasound is one of the most extensively researched technologies in the field of food processing. It is a novel fill in technology to thermal processing of foods. It involves use of lower frequencies of ultrasound (20–100 kHz) at much higher intensities (typically in the range of 10–1000 Wcm$^{-2}$). It brings about changes in food through cavitation mechanism and finds varied application within the field of food processing like homogenization, sterilization of liquid foods, enzyme inactivation and extraction of bioactives as summarised in Table 3.

Acoustic cavitation in food can be generated in two different ways firstly water bath and then probe sonicator. This technique is regarded as one most advantageous process owing to its less energy usage, reduced processing time and being environmentally friendly (Tiwari et al. 2008). The work of Sun et al. (2015) using probe sonicator in apple juice at treatment conditions of 10 min at 180 W input power and temperature of 15 °C in pulsed mode of 2 s on and 2 s off yielded the result that ultrasound helps in inhibition of browning in fresh apple juice but the results of PPO and POD activity were in contradiction to their hypothesis where they have claimed an in decrease in activity of enzyme. The trials also revealed that there was a decrease in the content of total phenolic content (TPC), total flavonoids content (TFC) and chlorogenic acid and reduced the antioxidant activity. The work of Abid et al. (2013) gave different perception about the effect of ultrasound on bioactive constituents of apple juice, there apple juice was treated at 25 kHz frequency at 20 °C between time trials 0–90 min. Sonication significantly improved

**Table 3** Effect of sonication processing on different characteristics of apple juice

| Attributes studied | Sonication processing conditions | Significant outcome | Improved quality attributes | Reference |
|---|---|---|---|---|
| **Browning & Bioactive contents** | 180 W for 10 min. at 15 °C | inhibited browning but decreased TPC and antioxidant activity | Inhibited Browning | (Sun et al. 2015) |
| **Bioactive constituents, cloud value and microbial content** | 25 kHz at 20 °C between 0 and 90 min. | Significantly improved TPC, Ascorbic acid, Cloud value, antioxidant content of juice and reduction in microbial content was observed | Improved photochemical composition, cloud value and extended shelf life | (Abid et al. 2013) |
| **Bioactive, micronutrient & rheological property** | 25 kHz & 70% amplitudes at 20 °C between 0 and 60 min. | Bioactive constituents, mineral content and viscosity of sonicated apple juice increased | Increased bioactive constituents, micronutrient content and improved sensorial attributes. | (Abid et al. 2015) |
| **Eznyme activity, microbial content and phytochemical composition** | Thermosonicated using ultrasound in-bath (25 kHz, 30 min, 0.06Wcm$^{-3}$) and ultrasound with-probe sonicator (20 kHz, 5 and 10 min, 0.30Wcm$^{-3}$) at 20, 40 and 60 °C | Inactivation of enzymes and microbe at 60 °C using probe sonicator for 10 mins. Retention of bioactives was higher in probe sonication method than ultrasound bath. | Inactivated enzymes & microbiota. Retention of bioactives was observed. | (Abid, Jabbar, Hu, Hashim, Wu, Wu, & Zeng 2014) |
|  | Treated at various amplitude levels (50 and 100 µm), pulses durations (50 and 100%), and temperatures (40, 50 and 60 °C). | It increased cloudiness and stability. Yeast and mold were completely inactivated. | Improved cloudiness and stability of juice. Extended shelf life by inactivation of microbiota. | (Ertugay and Başlar 2014) |

*TPC* total phenolic content

TPC, Ascorbic acid, Cloud value, antioxidant content of juice and significant reduction in microbial content was observed. Similar work of Abid et al. (2015) revealed that bioactive constituents, mineral content and viscosity of sonicated apple juice increased and in this trial apple juice was treated at 25 kHz and amplitude 70% with treatment time 0–60 min. This methodology has been well appreciated within consumers as they are providing quality and safety product at affordable cost and their ability to provide varied applications in the field of food processing have made researchers look up this field more extensively.

### *HPH*

High Pressure Homogenization (HPH) is a widely used technique to produce emulsions with varying droplet sizes and emerges out be a promising non thermal technique to process fruit juices. The pressure applied is in range of several 100 bars and fluids are forced through constriction. Their mechanism involves a combination of spatial pressure and velocity gradients, turbulence, impingement, cavitation and viscous shear, which leads to the microbial cell disruption and food constituent modification during the HPH process as summarised in Table 4. *Escherichia coli* K-12 was inactivated in apple juice using HPH process at pressure range of 100–200 MPa (Kumar et al. 2009). HPH process is known for its ability to reduce pulp sedimentation, produce uniform particle size improve cloud value & cloud stability. The cloud value and stability of the cloud apple juice are major quality parameters and can be determined spectrophotometrically. This fact was supported by the work of Zhu et al. (2019) where they treated apple juice between 10 and 50 MPa for one or two pass and they found better results at 20 MPa one pass where the apple juice showed lower cloud value, higher cloudy stability, more uniform particle sizes, higher ζ-potential and lower dynamic instability. Suárez-Jacobo et al. (2011) studied the impact of ultra-high homogenization at pressure of 100–300 MPa with an inlet temperature of 4 and 20 °C on antioxidant capacity, polyphenol and vitamin content of clear apple juice. The results revealed that HPH at 300 MPa preserved better bioactive nutrients in apple juice compared to thermal treatment. HPH is a quite a stable technology whose benefits are still to explored more in the field of food preservation.

### *Hydrodynamic cavitation*

Hydrodynamic Cavitation (HC) is a budding novel non thermal technique applied in the field of food process technology. This process is more or less similar to HPH process. Hydrodynamic cavitation is generated by passing the liquid through a constricted surface, where the cavities are generated due to a fall in the threshold pressure below the vapour pressure of the liquid. Increase in pressure at the time of exit through vena contracta results in collapse of cavity at that time. This results in hike energy as localized pressure (100–5000 bars) and temperature (1000–10,000 K) increases. This helps in microbial cell disruption, enzyme inactivation and also helps in improving the micronutrient availability and bioactive extraction (Gogate 2011a, b). HC process was first explored in the field of sterilization of liquids. The work of Milly et al. (2008), registered the fact that HC process enhanced the lethality of spoilage microorganisms. Using Shockwave Power reactor with a rotating pock-marked inner cylinder

**Table 4** Effect of HPH processing on different characteristics of apple juice

| Attributes studied | HPH Processing conditions | Significant outcome | Improved quality attributes | Reference |
|---|---|---|---|---|
| **Microbial content** | 100–200 MPa | Inactivation of *Escherichia coli* K-12. | Induced significant microbial inactivation | (Kumar et al. 2009) |
| **Homogenization and cloud stability** | 10–50 MPa | Better cloud stability, lower cloud value and more uniform particle size was found in apple juice. | Improved cloud stability of juice and decreased pulp sedimentation | (Zhu et al. 2019) |
| **Phytochemical Composition** | 100–300 MPa | Antioxidant capacity, polyphenol and vitamin content of clear apple juice was better preserved at 300 MPa than thermal pasteurization | Retention of bioactive is better preserved in HPH than thermal pasteurization. | (Suárez-Jacobo et al. 2011) |
| **Browning index and microbial content.** | Homogenization pressures from 100 to 300 MPa and inlet temperatures of 4 °C or 20 °C | Microbial count was less than < 1 log cfu/ml and stable for 2 months. Browning index and Hydroxymethylfurfural content were higher in thermally treated juice than HPH | Microbial inactivation and better retention of colour and less formation of Hydroxymethylfurfural compound in HPH treated juice. | (Saldo et al. 2009) |

*HPH* high pressure homogenization

hydrodynamic cavitation was induced in apple juice. Rotation of 3000 and 3600 rpm of apple juice raised the product temperature from 20 to 65.6 or 76.7 °C and achieved a log reduction of 6.27 of *Saccharomyces cervisiae*. HC is one of the cost effective and energy efficient methods to produce cavitation. This technology can also be scaled up at industrial level more easily than other novel technologies.

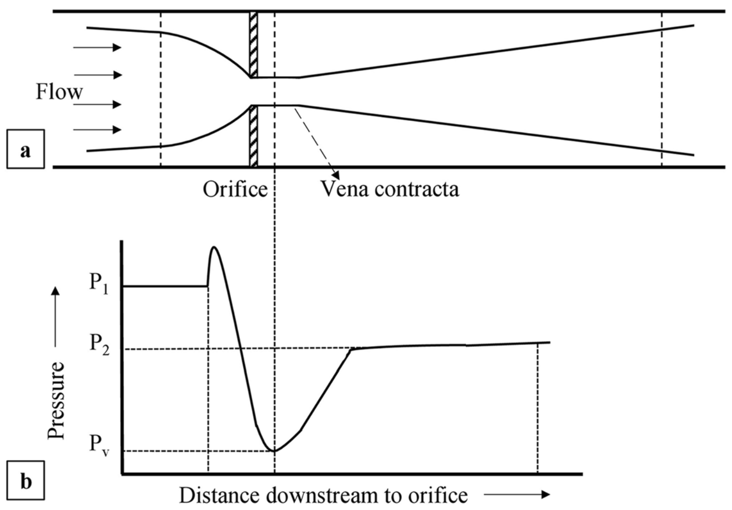
In recent trends HC is looked upon as a serious alternative to the acoustic cavitation for escalation of different physical and chemical processing applications because of generation of hotspots and turbulence generated within liquid system. Earlier HC application in processing liquid system was restricted owing to its corrosive effect on surface wall of the system. With pace of time these detrimental effects of HC cavitator were improved by altering the design and controlled application. HC success over acoustic cavitation was defined by its energy efficiency and in recent times many researchers explored its potential application in various fields of science. Interaction effect of velocity and change in pressure, results in formation of cavities in fluid system. Differential pressure energy results in formation of bubble, followed by its growth and eventually their collapse. All these processes are intentionally made in liquid system by varying the flow rate and pressure. This entire process occurs in very short period of time (milliseconds) and large of amount of energy is dissipated into fluid during collapse of cavities. It forms hotspots with localized high pressure (100–5000 bars) and temperature (1000–10,000 K) in multiple spots in the reactor aiding in elimination of deteriorative enzymes and microbiota (Gogate 2011a, b). Cavitation in system can be generated by four different mechanisms and they are classified based on the mode of their generation. It includes particle, optic, acoustic and hydrodynamic cavitation. Particle and optic cavitation generate single bubble cavitation in the system and this type of cavitation doesn't not induce any chemical or physical changes in fluid system. This mode of cavitation finds its application in surface cleaning and luminescence since collapse of single cavity doesn't uniformly raise the temperature of bulk system. Only acoustic and hydrodynamic mode of cavitation favours food industry. Acoustic cavitation involves use of ultrasound waves to induce cavitation in the system for its ability to concentrate energy into small volumes. Oscillation of sound waves induce physical stresses in a medium like collapse of bubbles, shock waves and formation of impinging jets in liquid system. Cavitation through hydraulic mode is achieved by passing the liquid through a small constriction like venturi meter, orifice meter or throttling valves. HC technique is one the most energy efficient and cost-effective method that can be utilized for generation of cavities. It also offers advantage over acoustic cavitation in terms of industry scalability, energy efficiency and cost. HC offers wide range of application related to food prospects like sterilization, microbial cell disruption, waste water management and extraction of bioactives (Arya et al. 2020).

*Principle and mechanism of hydrodynamic cavitation* Cavitation Number (σ) is the term associated with measuring the intensity of efficacy of cavitation given by Eq. 1. Efficacy of treatment is inversely proportionally to cavitation number, lower the cavitation number higher is the efficacy. Ideally the cavitation inception occurs at σ =1, but practically it generally occurs at a higher cavitation number (2–4). For efficient processing cavitation number should be maintained between 0.1–1 and very low cavitation numbers can lead to super cavitation. So, it is necessary to carefully design the experimental conditions to achieve the desired chemical and physical changes in the juice. The variation in inlet pressure and velocity can be adjusted to suite the desired cavitation number based on the type of reactor (Gogate 2011a, b). Cavitation generated through hydraulic means are governed by Bernoulli's equation which states that when liquid flows through a constriction a velocity increases with a drop in pressure. When drop in pressure falls below the vapour pressure of fluid, vapours are formed and as a result bubbles are formed. Through the passage of time, the cavities formed grow into bigger cavities and ultimately collapse when ambient pressure exceeds the vapour pressure (Fig. 1). Collapse of microbubbles results in formation of hotspots, shock waves in the entire bulk system of solution. It also generates free radicals and reactive species in the system. Heat is built up in the system due to friction between layers and this thermal heat dissipated along with other mechanisms mentioned above, tends to have lethal effect on the microbiota and deteriorative enzymes present in solution (Asaithambi et al. 2019)

$$\sigma = \frac{P_{ref} - P_v}{0.5\, x \rho V^2} \tag{1}$$

Where $P_{ref}$ is the reference pressure of flow liquid, $P_v$ is the liquid vapour pressure and V is the velocity of liquid.

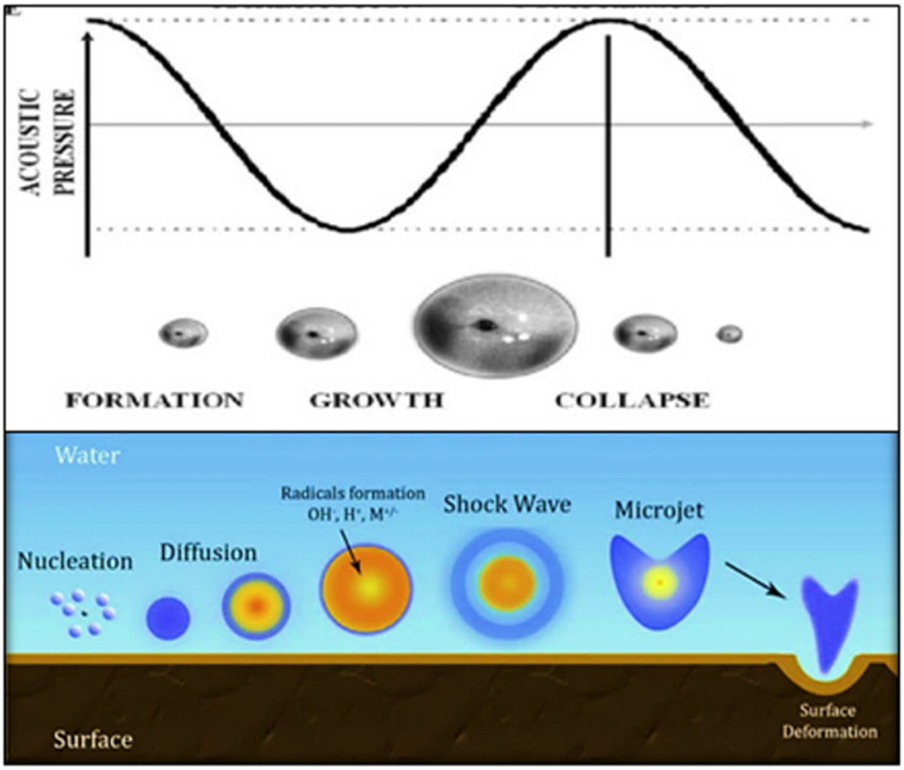
Hydrodynamic Cavitation has lethal effect on microbiota and enzymes and their mechanism includes physical and chemical stress induced in the system by cavitation as depicted in Fig. 2. Collapse of bubbles induces shock waves and create an impingement force on the cells in the system. Rarefactions and compression of shock waves results in breakage of water layer of hydration enzymes. Reactive species and free radicals generated during cavitation have



(a) The vena contracta of the cavitation assembly at which the actual pressure drop occurs; (b) Graphical representation of the pressure drop across vena contracta.

$P_v$ = vapour pressure of the liquid

**Fig. 1** Pressure variation inside vena contracta of the cavitation assembly [adapted from (Khaire & Gogate 2021)]



In cavitation the waves of compression and rarefaction are created in the liquid which are representative of high and low pressure regions respectively. In compression wave, the molecules are compressed tightly while in rarefaction wave the molecules are pulled apart rapidly.

At low pressure cycle, the dissolved air molecules diffuse to form bubbles. This is followed by the compression of the bubble and matter inside the bubble by the external pressure. The cycle of bubble growth and compression continues until the external pressure dominates and finally the bubble collapses

**Fig. 2** Different inactivation mechanisms, growth of bubble and subsequent bursting in cavitation phenomenon [adapted from (Pokhrel et al. 2016)]

**Table 5** Application of hydrodynamic cavitation in food systems

| S. No | Application | Treatment | Observation | Reference |
|---|---|---|---|---|
| 1 | **Sterilization** | Varied the flow rates and rotor speed of reactor at constant inlet pressure of 345 KPa. | Around 3 and 2.5 log reduction were achieved in tomato juice and skim milk respectively. Commercial sterility was achieved in Calcium fortified apple juice. | (Milly et al. 2007) |
| | | Treatment using venturi and orifice type plate at varying σ, temperature and processing time. | Achieved 90% lethality of yeast strains at low temperature and less energy input. | (Albanese et al. 2015) |
| 2 | **Homogenization** | Varying inlet pressure (5–7 bar pressure) and treatment time. | Reduced the fat particle to nanoscale | (Crudo et al. 2014) |
| | | Varying inlet pressure (400–800 Psi) and distance between orifice plate | Emulsion droplet (Palm oil based) size was reduced to 476 nm. | (Parthasarathy et al. 2013) |
| 3 | **Improvement in rheological property** | Varying the rotor speed and frequency of HC | Improved the firmness and viscosity of yoghurt samples. | (Meletharayil et al. 2016) |
| | | Treated using venturi, slit, and orifice type plates | Optimized condition resulted in 70% drop in viscosity | (Prajapat & Gogate 2015) |
| 4 | **Enhancement of Nutritional and Bioactive Content** | Varied the number of holes in reactor and temperature | At optimized condition bound phenolics and antioxidant content of sorghum flour and pomace increased. | (Lohani et al. 2016) |
| | | Varied the inlet pressure, temperature and number of passes. | Bioavailability and stability of carotenoid in carrot juice improved. | (Liu et al. 2019) |
| 5 | **Improving the stability** | Pressure drop (3–0.3 bar) at varying holding temperature | HC treated tomato juice exhibited higher stability without sedimentation for 14 days and did not alter the bioactive content of juice. | (Hilares et al. 2019) |
| 6 | **Shelf-Life Extension** | Using Hydro thermodynamic processing line | Heat resistant molds were inactivated and shelf life of blueberry juice was extended to 24 weeks. | (Fan et al. 2018) |

*HC* hydrodynamic cavitation

**Table 6** Effect of different non-thermal technologies on the quality of apple juice

| S. No | Non-Thermal Technique | Treatment Parameters | Changes in Quality of Apple Juice | References |
|---|---|---|---|---|
| 1 | **High Hydrostatic Pressure Processing** | 400 MPa 25 °C | Inactivation of *Escherichia coli* 29,055 and achieved more than 5 log reduction | (Ramaswamy et al. 2003) |
| | | 0.1–700 MPa & 20–80 °C | Synergistic effect on PPO inactivation above 300 MPa | (Buckow et al. 2009) |
| | | US-HPP 450 MPa | Inactivated PPO and microbial content and improved bioactive contents (TPC & antioxidants) | (Abid, Jabbar, Wu, Hashim, Hu, Lei, & Zeng 2014) |
| 2 | **Pulsed Electric Field** | 18–30 kV/cm & 86–172 µs | Inactivated Different strains of E.*Coli* and achieved 5 log reductions. Temperature was maintained below 35 °C | (Evrendilek et al. 1999) |
| | | 38.5 kV/cm and 300 µs at 50 °C | 70% inactivation of PPO and retained physiochemical and biochemical properties | (Sanchez-Vega et al. 2009) |
| | | 40 kV/cm for 100 µs + 50 °C | 70% inactivation of PPO and POD in apple juice | (Riener et al. 2008) |
| 3 | **Hydrodynamic Cavitation** | 3000–3600 rpm using shock wave power reactor. | 6.27 log reduction of *Saccharomyces cervisiae.* | (Milly et al. 2008) |
| 4 | **Cold Plasma** | Plasma at 10.5 kV for 5 mins | Inactivated around 84% PPO and enhanced TPC by 64% | (Illera et al. 2019) |
| 5 | **Pulsed Light** | 2.4 J/cm$^2$–71.6 J/cm$^2$ at interval for 3 s | 5.8 log cycle reduction of *S. cervisiae* in apple juice. | (Ferrario et al. 2015) |
| 6 | **Ozone Processing** | 1–4.8% (w/w) & processing time 0–10 min | Degraded the colour, rheological properties and phenolic content of apple juice | (Torres et al. 2011) |

*PPO* polyphenol oxidase, *POD* peroxidase, *TPC* total phenolic content potential to cause oxidation or reduction of cellular membranes. Enzyme protein structure is denatured due to collapse of cavity which results in localized high temperature and their native structure is also altered by hot gases which are capable of cleaving molecular bonds. As a result of this, native protein activity is lost and its detrimental effect on food system is reduced. Similar mechanism is adopted for inactivation of microbiota. Rarefactions and water jet induce perforation in outer membrane of cell wall in microbiota resulting in loss of periplasmic proteins and followed by that reactive species and free radicals oxidize cytoplasmic cell organelles. Both physical and chemical stress had a synergistic impact on the inactivation of microbiota (Arya et al. 2020; Asaithambi et al. 2019; Gogate 2011a, b).

*Application of hydrodynamic cavitation in food system* In recent times hydrodynamic cavitation processes are being explored in all spheres of food system since the technology is cost effective, easy to handle and scalable at industry level. The applications of HC in food systems is summarised in Table 5.

### Other techniques

Other novel methodologies to process fresh juice include ozone, UV, pulsed light and cold plasma. Table 6 summarises the effect of different non-thermal technologies on quality of apple juice.

## Conclusion and future prospectus

The minimal processing methods resulting in the retention of nutrition, quality and shelf life has been a challenge in a juice industry for a while now. This review deals with the potential of such different non thermal processes in maximising the nutritional output and shelf life of apple juice; and at the same time deals with the ease of operation and economic feasibility of a process. Inactivation of *Escherichia coli* 29,055 and PPO, reduction of *Saccharomyces cervisiae,* retention of colour and phytochemicals, and extension in shelf life to a different degrees at different given conditions can successfully be achieved through the reviewed process operations.

Different non thermal techniques and processes, alone or in combination with other processes have been tried for fruit juices and the favourable results have been achieved. To upscale any such process to an industry level the economic feasibility in terms of energy requirement and the ease of operation in handling the bulk volumes of juice at one time is still the question in place. If the upscale of any of these novel non thermal processes is dealt optimally and the promising results for minimal damage of bioactives and extension in shelf life of fruit juices is successfully achieved; these techniques have the potential of replacing the thermal processes, that still remain the most extensively used fruit juice processing techniques.

**Acknowledgements**
None.

### Authors' contributions

Shalini. S. Arya: conceptualization, writing, reviewing and editing; Nachal Nachiappan: acquisition, writing original draft; Roji Waghmare: conceptualization, reviewing and editing Mohmad Sayeed Bhat: writing, reviewing and editing. The author(s) read and approved the final manuscript.

**Funding**
Not applicable.

### Availability of data and materials

The data used in this review is available online and can be accessed through scientific databases.

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors have no competing interest.

**Author details**
[1]Food Engineering and Technology Department, Institute of Chemical Technology (formerly UDCT/UICT), Nathalal Parekh Marg, Matunga, Mumbai 400 019, India. [2]Department of Food Engineering, College of Food Technology, Dr. Punjabrao Deshmukh Krishi Vidyapeeth, Yavatmal, Maharashtra 445001, India.

Received: 10 May 2022 Accepted: 28 February 2023

### References

Abid, M., Jabbar, S., Hu, B., Hashim, M. M., Wu, T., Lei, S., & Zeng, X. (2014). Thermosonication as a potential quality enhancement technique of apple juice. *Ultrasonics Sonochemistry*, *21*(3), 984–990.

Abid, M., Jabbar, S., Hu, B., Hashim, M. M., Wu, T., Wu, Z., & Zeng, X. (2014). Synergistic impact of sonication and high hydrostatic pressure on microbial and enzymatic inactivation of apple juice. *LWT-Food Science and Technology*, *59*(1), 70–76.

Abid, M., Jabbar, S., Wu, T., Hashim, M. M., Hu, B., Lei, S., & Zeng, X. (2013). Effect of ultrasound on different quality parameters of apple juice. *Ultrasonics Sonochemistry*, *20*(5), 1182–1187.

Abid, M., Jabbar, S., Wu, T., Hashim, M. M., Hu, B., Lei, S., & Zeng, X. (2014). Sonication enhances polyphenolic compounds, sugars, carotenoids and mineral elements of apple juice. *Ultrasonics Sonochemistry*, *21*(1), 93–97.

Abid, M., Jabbar, S., Wu, T., Hashim, M. M., Hu, B., Saeeduddin, M., & Zeng, X. (2015). Qualitative assessment of sonicated apple juice during storage. *Journal of Food Processing and Preservation*, *39*(6), 1299–1308.

Albanese, L., Ciriminna, R., Meneguzzo, F., & Pagliaro, M. (2015). Energy efficient inactivation of S accharomyces cerevisiae via controlled hydrodynamic cavitation. *Energy Science & Engineering*, *3*(3), 221–238.

Arya, S. S., Sawant, O., Sonawane, S. K., Show, P. L., Waghamare, A., Hilares, R., & Santos, J. C. D. (2020). Novel, nonthermal, energy efficient, industrially scalable hydrodynamic cavitation–applications in food processing. *Food Reviews International*, *36*(7), 668–691.

Asaithambi, N., Singha, P., Dwivedi, M., & Singh, S. K. (2019). Hydrodynamic cavitation and its application in food and beverage industry: A review. *Journal of Food Process Engineering*, *42*(5), e13144.

Buckow, R., Weiss, U., & Knorr, D. (2009). Inactivation kinetics of apple polyphenol oxidase in different pressure–temperature domains. *Innovative Food Science & Emerging Technologies*, *10*(4), 441–448.

Charles-Rodríguez, A. V., Nevárez-Moorillón, G. V., Zhang, Q. H., & Ortega-Rivas, E. (2007). Comparison of thermal processing and pulsed electric fields treatment in pasteurization of apple juice. *Food and Bioproducts Processing*, *85*(2), 93–97.

Crudo, D., Bosco, V., Cavaglia, G., Mantegna, S., Battaglia, L. S., & Cravotto, G. (2014). Process intensification in the food industry: Hydrodynamic and acoustic cavitation in fresh milk treatment. *Agro Food Industry Hi-Tech, 25*, 55–59.

Ertugay, M. F., & Başlar, M. (2014). The effect of ultrasonic treatments on cloudy quality-related quality parameters in apple juice. *Innovative Food Science & Emerging Technologies*, *26*, 226–231.

Evrendilek, G. A., Zhang, Q. H., & Richter, E. R. (1999). Inactivation of Escherichia coli O157: H7 and Escherichia coli 8739 in apple juice by pulsed electric fields. *Journal of Food Protection*, *62*(7), 793–796.

Fan, L., Martynenko, A., Doucette, C., Hughes, T., & Fillmore, S. (2018). Microbial quality and shelf life of blueberry purée developed using cavitation technology. *Journal of Food Science*, *83*(3), 732–739.

Ferrario, M., Alzamora, S. M., & Guerrero, S. (2015). Study of the inactivation of spoilage microorganisms in apple juice by pulsed light and ultrasound. *Food Microbiology*, *46*, 635–642.

Gliszczynska-Swiglo, A. A. G. A., & Tyrakowska, B. (2003). Quality of commercial apple juices evaluated on the basis of the polyphenol content and the TEAC antioxidant activity. *Journal of Food Science*, *68*(5), 1844–1849.

Gogate, P. R. (2011a). Application of hydrodynamic cavitation for food and bioprocessing. In *Ultrasound technologies for food and bioprocessing*, (pp. 141–173). Springer.

Gogate, P. R. (2011b). Hydrodynamic cavitation for food and water processing. *Food and Bioprocess Technology*, *4*(6), 996–1011.

Gupta, R., & Balasubramaniam, V. M. (2012). High-pressure processing of fluid foods. In P. J. Cullen, B. K. Tiwari, & V. P. Valdramidis (Eds.), *Novel thermal and non-thermal technologies for fluid foods*, (pp. 109–128). Academic Press.

Heinz, V., Toepfl, S., & Knorr, D. (2003). Impact of temperature on lethality and energy efficiency of apple juice pasteurization by pulsed electric fields treatment. *Innovative Food Science & Emerging Technologies*, *4*(2), 167–175.

Hilares, R. T., Dos Santos, J. G., Shiguematsu, N. B., Ahmed, M. A., da Silva, S. S., & Santos, J. C. (2019). Low-pressure homogenization of tomato juice using hydrodynamic cavitation technology: Effects on physical properties and stability of bioactive compounds. *Ultrasonics Sonochemistry*, *54*, 192–197.

Illera, A. E., Chaple, S., Sanz, M. T., Ng, S., Lu, P., Jones, J., … Bourke, P. (2019). Effect of cold plasma on polyphenol oxidase inactivation in cloudy apple juice and on the quality parameters of the juice during storage. *Food Chemistry: X*, *3*, 100049.

Khaire, R. A., & Gogate, P. R. (2021). Application of hydrodynamic cavitation in food processing. In *Design and optimization of innovative food processing techniques assisted by ultrasound*, (pp. 317–342). Academic Press.

Krapfenbauer, G., Kinner, M., Gössinger, M., Schönlechner, R., & Berghofer, E. (2006). Effect of thermal treatment on the quality of cloudy apple juice. *Journal of Agricultural and Food Chemistry*, *54*(15), 5453–5460.

Kumar, S., Thippareddi, H., Subbiah, J., Zivanovic, S., Davidson, P. M., & Harte, F. (2009). Inactivation of Escherichia coli K-12 in apple juice using combination of high-pressure homogenization and chitosan. *Journal of Food Science*, *74*(1), 8–14.

Lee, C. Y. (2012). Common nutrients and nutraceutical quality of apples. *New York Fruit Quarterly*, *20*(3), 1–8.

Liu, X., Liu, J., Bi, J., Yi, J., Peng, J., Ning, C., & Zhang, B. (2019). Effects of high pressure homogenization on pectin structural characteristics and carotenoid bioaccessibility of carrot juice. *Carbohydrate Polymers*, *203*, 176–184.

Lohani, U. C., Muthukumarappan, K., & Meletharayil, G. H. (2016). Application of hydrodynamic cavitation to improve antioxidant activity in sorghum flour and apple pomace. *Food and Bioproducts Processing*, *100*, 335–343.

Markowski, J., Baron, A., Le Quéré, J. M., & Płocharski, W. (2015). Composition of clear and cloudy juices from French and polish apples in relation to processing technology. *LWT-Food Science and Technology*, *62*(1), 813–820.

Massini, L., Rico, D., & Martin-Diana, A. B. (2018). Quality attributes of apple juice: Role and effect of phenolic compounds. In *Fruit juices*, (pp. 45–57). Academic Press.

Meletharayil, G. H., Metzger, L. E., & Patel, H. A. (2016). Influence of hydrodynamic cavitation on the rheological properties and microstructure of formulated Greek-style yogurts. *Journal of Dairy Science*, *99*(11), 8537–8548.

Milly, P. J., Toledo, R. T., Harrison, M. A., & Armstead, D. (2007). Inactivation of food spoilage microorganisms by hydrodynamic cavitation to achieve pasteurization and sterilization of fluid foods. *Journal of Food Science*, *72*(9), 414–422.

Milly, P. J., Toledo, R. T., Kerr, W. L., & Armstead, D. (2008). Hydrodynamic cavitation: Characterization of a novel design with energy considerations for the inactivation of Saccharomyces cerevisiae in apple juice. *Journal of Food Science*, *73*(6), 29.

Moyer, J. C., & Aitken, H. C. (1980). Apple juice. In P. E. Nelson, & D. K. Tressler (Eds.), *Fruit and vegetable juice processing technology*, (pp. 212–267). AVI.

Needs, E. C., Stenning, R. A., Gill, A. L., Ferragut, V., & Rich, G. T. (2000). High-pressure treatment of milk: Effects on casein micelle structure and on enzymic coagulation. *Journal of Dairy Research*, *67*(1), 31–42.

Oyenihi, A. B., Belay, Z. A., Mditshwa, A., & Caleb, O. J. (2022). An apple a day keeps the doctor away: The potentials of apple bioactive constituents for chronic disease prevention. *Journal of Food Science, 87*, 2291–2309.

Parthasarathy, S., Siah Ying, T., & Manickam, S. (2013). Generation and optimization of palm oil-based oil-in-water (O/W) submicron-emulsions and encapsulation of curcumin using a liquid whistle hydrodynamic cavitation reactor (LWHCR). *Industrial & Engineering Chemistry Research*, *52*(34), 11829–11837.

Pokhrel, N., Vabbina, P. K., & Pala, N. (2016). Sonochemistry: Science and engineering. *Ultrasonics Sonochemistry*, *29*, 104–128.

Prajapat, A. L., & Gogate, P. R. (2015). Intensification of depolymerization of aqueous guar gum using hydrodynamic cavitation. *Chemical Engineering and Processing: Process Intensification*, *93*, 1–9.

Ramaswamy, H. S., Riahi, E., & Idziak, E. (2003). High-pressure destruction kinetics of E. coli (29055) in apple juice. *Journal of Food Science*, *68*(5), 1750–1756.

Renard, C. M., Le Quéré, J. M., Bauduin, R., Symoneaux, R., Le Bourvellec, C., & Baron, A. (2011). Modulating polyphenolic composition and organoleptic properties of apple juices by manipulating the pressing conditions. *Food Chemistry*, *124*(1), 117–125.

Riener, J., Noci, F., Cronin, D. A., Morgan, D. J., & Lyng, J. G. (2008). Combined effect of temperature and pulsed electric fields on apple juice peroxidase and polyphenoloxidase inactivation. *Food Chemistry*, *109*(2), 402–407.

Rupasinghe, H. V., & Yu, L. J. (2012). Emerging preservation methods for fruit juices and beverages. *Food additive*, 65–82.

Saldo, J., Suárez-Jacobo, Á., Gervilla, R., Guamis, B., & Roig-Sagués, A. X. (2009). Use of ultra-high-pressure homogenization to preserve apple juice without heat damage. *High Pressure Research*, *29*(1), 52–56.

Sanchez-Vega, R., Mujica-Paz, H., Marquez-Melendez, R., Ngadi, M. O., & Ortega-Rivas, E. (2009). Enzyme inactivation on apple juice treated by ultrapasteurization and pulsed electric fields technology. *Journal of Food Processing and Preservation*, *33*(4).

Starowicz, M., Achrem-Achremowicz, B., Piskuła, M. K., & Zieliński, H. (2020). Phenolic compounds from apples: Reviewing their occurrence, absorption, bioavailability, processing, and antioxidant activity – A review. *Polish Journal of Food and Nutrition Sciences*, *70*(4), 321–336.

Suárez-Jacobo, Á., Rüfer, C. E., Gervilla, R., Guamis, B., Roig-Sagués, A. X., & Saldo, J. (2011). Influence of ultra-high pressure homogenisation on antioxidant capacity, polyphenol and vitamin content of clear apple juice. *Food Chemistry*, *127*(2), 447.

Sun, Y., Zhong, L., Cao, L., Lin, W., & Ye, X. (2015). Sonication inhibited browning but decreased polyphenols contents and antioxidant activity of fresh apple (malus pumila mill, cv. Red Fuji) juice. *Journal of Food Science and Technology*, *52*(12), 833.

Tiwari, B. K., Muthukumarappan, K., O'donnell, C. P., & Cullen, P. J. (2008). Colour degradation and quality parameters of sonicated orange juice using response surface methodology. *LWT-Food Science and Technology*, *41*(10), 1876–1883.

Torres, B., Tiwari, B. K., Patras, A., Wijngaard, H. H., Brunton, N., Cullen, P. J., & O'Donnell, C. P. (2011). Effect of ozone processing on the colour, rheological properties and phenolic content of apple juice. *Food Chemistry*, *124*(3), 721–726.

U.S. Department of Agriculture (USDA) (2014). *USDA National Nutrient Database for standard reference, release 27*. National Technical Information Service, USDA.

U.S. Food and Drug Administration (2001). Hazard analysis and critical control point (HACCP); procedures for the safe and sanitary processing and importing of juices; final rule. *Federal Register*, *66*, 6138–6202.

Wojdyło, A., Nowicka, P., Turkiewicz, I. P., Tkacz, K., & Hernandez, F. (2021). Comparison of bioactive compounds and health promoting properties of fruits and leaves of apple, pear and quince. *Scientific Reports*, *11*(1), 1–17.

Zhu, D., Kou, C., Wei, L., Xi, P., Changxin, L. V., Cao, X., & Liu, H. (2019). Effects of high-pressure homogenization on the stability of cloudy apple juice. In IOP conference series: Earth and environmental science (358 (2), pp. 0220.

## Publisher's Note