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Emerging non-thermal processing techniques for preservation of tender coconut water

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ABSTRACT

Tender coconut water (TCW) possesses appreciable nutritional and health-promoting benefits. The high nutritional potential of the drink had raised the overall demand globally among the consumers. Nevertheless, the processing and appropriate shelf-life extension is significant hurdles in tapping the nutritional potential of TCW. Besides, the possible chance of enzymatic browning and the associated biochemical reactions impart unfavorable effects to the TCW quality parameters. Although thermal processing techniques are being widely explored, their inherent limitation and the generation of off-flavor and discoloration urge to explore alternative non-thermal techniques. The major mechanism of non-thermal techniques behind enzyme inactivation and antimicrobial effect is the conformational change of protein structure and cell destruction, respectively. In this review, the application of non-thermal techniques *viz.* ozone technology, high-pressure processing, filtration, ultrasound, ultraviolet, cold plasma, pulsed light, and electric field treatments are explored and compared.

1. Introduction

Coconut (*Cocos nucifera* L) is a fibrous fruit loaded with numerous minerals, electrolytes, ions, and sugars as well. It has pleasing organoleptic attributes and low calories (Ribeiro, Valdramidis, Nunes, & de Souza, 2017; Rojas, Trevilin, dos Santos Funcia, Gut, & Augusto, 2017). Tender coconut fruit is a spherical-shaped drupe that has an outer layer (exocarp) of thick fibers (mesocarp), enclosing the hard outer shell (endocarp), and internally followed by a white fleshy kernel (endosperm) filled with the nutrient-rich coconut water. India is one of the leading countries in coconut production. The overall coconut production data in India during 2018–19 reveals that 2150 ha of land are under coconut cultivation with the productivity of 9897 nuts/ha (CDB Statistics, 2018). The sweet, nutritious water present in the coconut is a liquid endosperm covering about 25% of its total weight (Naik, CK, & Rawson, 2020). Tender coconut water (TCW), Coconut water (CW), and Green coconut water (GCW) have been synonymously used in numerous studies to denote the liquid endosperm of coconut. All the three terms differ in certain aspects, mostly indicating their maturity and variety. TCW refers to the water when the nut reaches 7–9 months of maturity, and the liquid at this time tastes the sweetest and is also termed as young coconut water (Tetra Pack., 2019). The water from a nut that is 10–13 months old is the mature coconut water or referred to as CW, whereas the water derived from a variety called green dwarf or green coconut is called GCW (Dwiloka, Rizqiati, & Setiani, 2020; Tetra Pack, 2019, pp. 1–183). However, on some occasions, it is observed that TCW and GCW are interchangeably used.

The preference for fresh TCW is gaining popularity among the consumers due to their nutritional aspects and consumer awareness about carbonated and artificial beverages. It is a healthy sports drink that has immense rehydration potential (Cappelletti et al., 2015). Coconut water exhibits reasonably high therapeutic effects and may be used for relieving many ailments (Edison & Ann, 2018). It can be employed to mitigate urinary tract infections, stomach pain, prevent hot rashes, and helps maintain body pH level (Rajashri, Rastogi & Negi, 2020). Also, coconut water has similar characteristics as blood plasma, which

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encourages its use as a substitute (Rajashri, Rastogi et al., 2020). In addition, TCW intake safeguards the heart from myocardial infarction and reduces high blood pressure and hypertension. The TCW effectively alleviates severe diseases such as sickle cell anemia (Edison & Ann, 2018). However, overconsumption of TCW may increase the potassium levels in the blood that lead to kidney problem (https://www.webmd.com). Despite all its beneficiary qualities, the limited shelf life of the product is a stumbling block to its wide usage.

The action of food enzymes such as polyphenol oxidases (PPO) and peroxidases (POD) play a vital role in diminishing the storage life and market potential of TCW. Catalytic activities of both the enzymes develop many unappealing effects in TCW, even during refrigerated storages. Similarly, pink color formation, browning, awful flavors, and odors are certain objectionable outcomes of the catalytic functions and microbial activity (Rojas et al., 2017; Rajashri, Roopa, Negi, & Rastogi, 2020). Furthermore, the fresh TCW is highly susceptible to the attack of microorganisms such as *Clostridium botulinum* (Raghubeer et al., 2020).

TCW is highly sensitive to microbial attack within a few hours after its extraction from the nut, which in turn results in the loss of nutritional components as well as a shortened shelf-life (Mahnot et al., 2019; Ribeiro et al., 2017). Interestingly, it has been reported that certain inherent substances of TCW *viz.* antimicrobial peptides and lauric acids act as an inhibitor of the growth of the microbial strains (Raghubeer et al., 2020). Hence, it is imperative to preserve the superior quality drink of nutraceutical and sensorial importance. Thermal processing methods are the most commonly employed preservation techniques for TCW. Nevertheless, these treatments diminish the overall acceptance of the product and, at the same time, reduce their beneficiary qualities (Ribeiro et al., 2017).

Thermal processing methods such as evaporation, pasteurization, and sterilization in the food industry are the most energy-consuming technologies (Picart-Palmade, Cunault, Chevalier-Lucia, Belleville, & Marchesseau, 2019). Also, thermal treatments cause detrimental effects on color, clarity, and sensorial properties. The traditional thermal processing methods tend to alter the organoleptic properties due to the destruction of sensitive compounds, thereby altering the natural properties of the product. Hence, it is important to explore the non-thermal technologies for the preservation and shelf-life extension of TCW. Diverse state-of-the-art procedures have been introduced into the food processing and preservation sectors. Cold plasma (Mahnot, Mahanta, Farkas, ; Mahnot, Mahanta, Keener, et al., 2019), ultrasound (Rojas et al., 2017), ultraviolet (Gautam et al., 2017; Yannam et al., 2020), ozone (Vardharaju & Chandrasekar, 2016), high-pressure processing (Raghubeer et al., 2020), microfiltration (Mahnot, Gupta & Mahanta, 2019; Sumonsiri, 2019), and the combination of these treatments with mild heating have been successfully employed to enhance the storage life of TCW.

This review thus elaborates on the most recent techniques that have potentially been utilized to preserve TCW. Furthermore, we have compared highly efficient techniques and their synergistic effects with moderate heat treatments. Also, a proper understanding of the kinetics of TCW preservation will benefit the discovery of underlying inactivation mechanisms. In this context, various kinetic models describing the enzyme inactivation and microbial inactivation are discussed, compared, and the best fit has been well cited.

2. Emerging technologies

Non-thermal technologies on TCW are researched to solve the inherent limitations of conventional thermal processing. Although it is well recognized that thermal processing is very effective in causing enzyme inactivation and providing antimicrobial effects, the demand for the preservation of sensory and nutritional properties of produce after treatment urges the implementation of emerging non-thermal technologies. Emerging food processing technologies and combination of non-thermal technologies find application in the preservation of TCW and are in the line of commercialization. The effect of non-thermal technologies processing parameters on enzyme inactivation in TCW is shown in Table 1.

2.1. Ozone

Ozone is a popular oxidative treatment for food preservation that significantly provides a higher shelf life to the food matrix (Pandiselvam et al., 2017, 2019, 2020). The main hindrance in shelf-life extension is the catalytic activities of PPO and POD. Hence, these enzymes are targets for the treatment operations, which aim at reducing the enzymatic activities due to the oxidative changes in enzyme structure. This conformational change is characterized by the direct reaction with ozone or other reactive species, which causes crosslinking or segmentation in the molecule, as shown in Fig. S1. Also, reactive oxygen species react with amino acids, protein backbones, and side chains that result in enzyme destruction through protein fragmentation or destruction of protein crosslinks (Jaramillo Sánchez, Garcia Loredo, Contigiani, Gómez, & Alzamora, 2018).

Ozone concentration and exposure time are highly correlated with the retardation of enzyme activities. The application of ozone in combination with a bio-preservative (nisin) has successfully reduced the microbial population (*Escherichia coli*) and enzyme activities and simultaneously retaining nutritional compounds in TCW (Rajashri, Roopa et al., 2020). The combination of non-thermal technology followed by bio-preservative treatment was performed widely since the effect of bio-preservatives was aggravated due to improved cell penetration resulting from the preceding non-thermal treatments. Ozone gas dosages of 20 mg/L at flow rates of 1 L/min for up to 10 min exposure followed by the addition of nisin was suggested as a potential method that extended the shelf-life of TCW up to 3 weeks. Also, nisin molecules form a wedge-like pore bound to bacterial phospholipid membrane that enters into the cytoplasmic membrane and creates variations in electrical potential and pH gradient, ultimately leading to cell death of bacteria and enzymes (Sobrino-López & Martín-). The process did not cause any detrimental effects on the nutritional aspects of the sample. At the same time, it presented high sensorial acceptance. Furthermore, comparable results were acquired when green coconut water was ozonated within a range of 0.075–0.37 mg/L with varying times (Porto et al., 2020). Ozone treatments all the way increased the inactivation rate of peroxidases with a slight reduction in phenolic compounds and sensory quality (Porto et al., 2020). Moreover, both the investigations point out the inherent nature of lower-level ozone enrichment in the preservation of TCW. Additionally, processing variables *viz.* ozone concentration (50–100 μg/mL), exposure time (2–12 min), and storage period of 0–12 days at 4 °C in tender coconut water processing attained similar outcomes (Vardharaju & Chandrasekar, 2016). However, the physicochemical attributes of TCW showed remarkable changes with the increase in the gas concentrations and processing time. Low-level ozonation and synergistic effect with other food additives may provide promising results without compromising the quality of tender coconut water. However, the oxidizing nature of ozone can alter other desired components altering the sensorial characteristics of the product. In addition, ozone treatment can be combined with other processing techniques to obtain the desired effect of both technologies.

2.2. High-pressure processing (HPP)

HPP technology is of paramount importance in modern food processing methodologies. Many researchers have attempted the potential of HPP for the processing and preservation of TCW. Investigation with HPP treatments at 593 MPa for 3 min efficiently inhibited the microbial activity of *E. coli* O157:H7, *Salmonella* spp, and *L. monocytogenes* in coconut water (Raghubeer et al., 2020). The temperature of the samples and pressure medium during treatment was 4 °C. The treated samples could be successfully stored at refrigerated temperature (4 °C) for 120

Table 1

Enzyme inactivation and antimicrobial effect of non-thermal technologies on tender coconut water (TCW).

Treatment method	Specifications	Findings	Reference
Ohmic heating	Voltage-15 and 20 V/cm, temperatures-80, 90, 100 °C and holding times of 0, 1.5 and 3 min	TCW heated at 80 °C (20 V/cm) for 3 min had minimum residual PPO activity of 30.55 ± 0.92%	Aniesrani Delfiya and Thangavel
Pulsed light treatment	Pulsed light intensities of 0.18, 2 and 5.6 W/cm^2, and exposure time between 0 and 15 s	Intensities of 2 and 5.6 W/cm^2 attained inactivation of 4 log units of *E. coli*	Preetha et al. (2017)
Filtration	Non-thermal microfiltration (transmembrane pressures 21–193 kPa and cross flow rate 5–15 l/h).	Polyacrylonitrile of 44 kDa treated with sodium hydroxide with pressure 138 kPa and 15 l/h flow rate gained good results	Karmakar and De (2017)
	Nisin treatment on microfiltered samples (25–75 ppm nisin polyethersulfonepuradisc of 0.2 μm pore size and 25 mm diameter)	Microfiltered samples with 50 and 75 ppm nisin exhibited low microbial count with better sensory quality	Sumonsiri (2019)
	Acoustic field assisted ultrafiltration (Polyethersulfone membrane (30 and 100 kDa) pressures of 1, 2, 3 and 4.5 bar, acoustic field of 1.2 MHz)	Treatment with 30 kDa had reduced catalytic activity of PPO and POD by 95.10 and 97.89% respectively	Ochoa-Velasco et al. (2018)
	Non-thermal microfiltration with additives (0.8 and 0.45 μm pore size membrane, additives-200 mg/L citric acid, 180 mg/L ascorbic acid, orange honey at 5% (w/v)	Prescribed treatment with additives and packaging in glass bottles in nitrogen flushed atmosphere obtained sterile product up to 90 days of refrigerated storage	Mahnot, Gupta and Mahanta (2019)
Ultrasound (US)	As pre-treatments and applied alone (286 W/L acoustic density for 30 min and thermal processing at 80, 85 and 90 °C)	Peroxidase inactivation of 27% was obtained by US treatments.	Rojas et al. (2017)
Ultraviolet	400 W nominal power lamp with radiation wavelength between 400 and 420 nm	PPO and POD activities was reduced to approximately 2 and 1% after 30 min of processing	Augusto et al. (2015)
	Ultraviolet-C (wavelength-254nm, dosage-0 to 40mJ/cm^{-2})	40 mJ/cm^{-2} produced 5 log reduction in microbial populations	Bhullar et al. (2019)
	254 nm wavelength at a residence time of 14.0 s	Dean flow reactor UV-C treatment ably pasteurized TCW along with the retention of its physicochemical attributes	Gautam et al. (2017)
	18 W lamp with 200–300 nm wavelength, time- 1, 2, 3 min	Treatment caused major difference in colour but maintained pH, TSS, and titratable acidity	Sanganamoni et al. (2017)
High pressure processing (HPP)	HPP and HTST process (500 MPa pressure, 72 °C for 15 s)	Both processes extended shelf life to 25 and 15 days respectively with HPP having more nutrient retention	Ma et al. (2019)
	High pressures of 593 MPa for 3 min at temperature of 4 °C	Treatment conditions gave microbiologically stable product with high sensory score almost similar to fresh sample	Raghubeer et al. (2020)
Cold plasma treatment	Atmospheric cold plasma (ACP) produced in air and M65 (65% O_2, 30% CO_2, 5%N_2) were used as working gases) using dielectric barrier discharge of 0–120 kV	Microbial population was reduced (5 $\log_{10}$) in the study with M65 gas for 120 s at 90 kV with 400 ppm citric acid addition	Mahnot, Mahanta, Farkas,
	Voltage- 18 to 28 kV, time from 1 to 3 min	18.00 kV voltage and 1.75 min time applications along with 1% orange juice additions to TCW brought in product with acceptable sensory properties	Chutia et al. (2019)
	Atmospheric pressure plasma jet (450 and 650 W)	Inactivation of all test organism was higher at 650 W (1.86–3.11 min) compared to those at 450 W (2.76–5.98 min) and determined *S.enterica* as the target for jet plasma.	Gabriel et al. (2016)
Pressure assisted thermal processing	200, 400 and 600 MPa, 40–90 °C, and 60–1800 s of holding time	Enzyme activity was arrested completely at 90 °C with 400 MPa for 300 s yielded best results	Chourio et al. (2018)

PPO-Polyphenol oxidase; POD- Peroxidase.

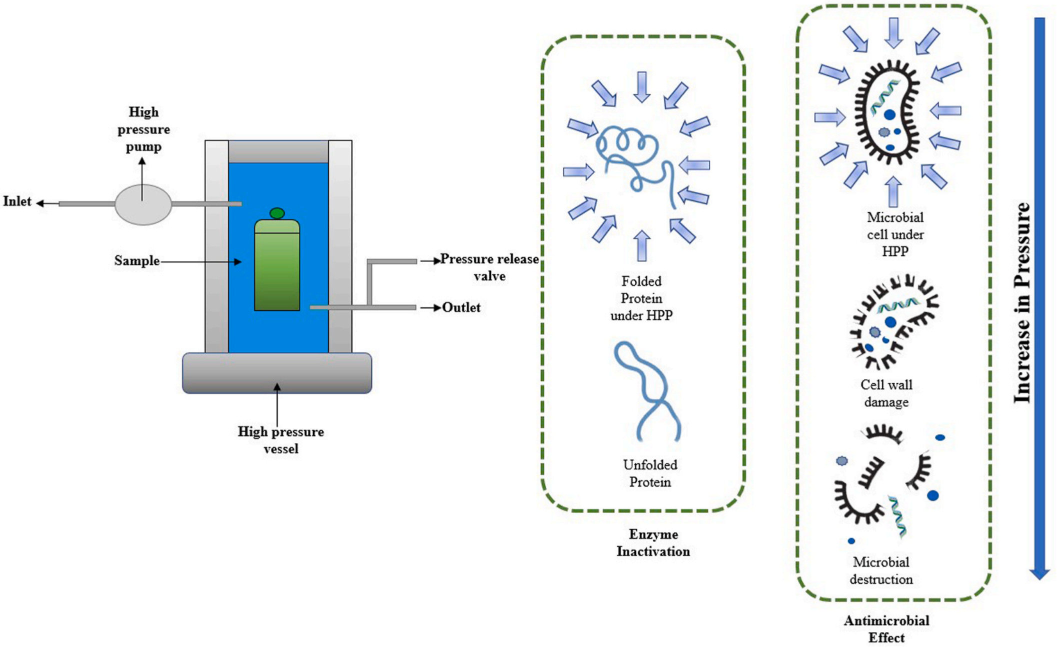

Fig. 1. Mode of action of High Pressure Processing (HPP) on food enzyme.

days without the development of any off-flavors. The HPP mode of action on the inactivation of enzymes is due to protein denaturation occurring during the application of pressure (Fig. 1). During this high-pressure process, the enzyme structure can get partially or fully unfolded, losing its specificity and capability to bind with substrates. Also, a significant change in the hydration volume causes denaturation under high-pressure conditions (Chakraborty, Kaushik, Rao, & Mishra, 2014).

It is also worth mentioning that the conformational changes can be either reversible or irreversible depending on the processing condition and commodity (Chakraborty et al., 2014). Also, refolding reversible subunits of a protein does not always guarantee the proper functioning of enzyme subunits (Chakraborty et al., 2014). Furthermore, similar conclusions were obtained when fresh coconut water was administered with high pressures of 500 MPa for 5 min (Ma et al., 2019). The treatment enhanced shelf life up to 25 days as well as prevented the formation of pink color by inactivating PPO and POD. Additionally, high-pressure technology reduced the microbial populations and, at the same time, retained 93.17% total phenolic content, 76.76% proteins, and 76.85% amino acids (Ma et al., 2019). The microbial inactivation was caused due to damage to of cell wall, cell membrane, and protein denaturation (Woldemariam & Emire, 2019). Besides, the enzyme inactivation will result in antimicrobial action due to the impeded functions of the enzymes (Woldemariam & Emire, 2019). Also, HPP products show less shelf stability than thermally treated ones, which might have occurred due to lesser enzymatic inactivation (Keenan, Rößle, Gormley, Butler, & Brunton, 2012). HPP had seven times larger expenses from a commercial perspective than conventional thermal treatments (Rajashri, Rastogi et al., 2020). Overall, the drawbacks of HPP need to be addressed by introducing new hurdles to the processing chain in order to retain the natural qualities of the products.

2.3. *Microfiltration*

Membrane filtration is an emerging technique in the food processing sector. Nevertheless, the scientific literature about TCW processing based on different microfiltration methodology is comparatively less. The underlying principle for microfiltration is the size difference or sieving effect created by the filtration element. During microfiltration, a suitable pore size for the filtering element should be selected so that the enzyme gets retained on the element and all other components are allowed to pass through (Mahnot, Gupta, & Mahanta, 2019). This technique is a cold sterilization process sometimes coupled with other thermal and non-thermal processing methods for desired results.

Ultrafiltration with pore size 0.002 to 0.1 μm is efficient in retaining enzymes on the feed side of the membrane, hence significantly diminishing their activity (Lamdande, Mittal, & Raghavarao, 2020). With added L-ascorbic acid, microfiltered coconut water has been proven to be a better alternative to thermal methods (Das et al., 2012). The concentrations of PPO and POD enzymes are reduced with an increasing concentration of ascorbic acid. Oxygen scavenging and the blockage of the active site of the enzyme catalyst could be attributed to the inactivation of enzyme activities (Das et al., 2012). However, a higher amount of the additive causes an increased acidic flavor in TCW, which consequently reduced the overall acceptability of the product. Moreover, comparable results were obtained by Mahnot, Kalita, Mahanta, and Chaudhuri (2014), where the degradation of microfiltered TCW was prevented by additives such as ascorbic and citric acid as well as L-cysteine. Additionally, on the packaging aspect, TCW in glass bottles had the most superior quality in all aspects compared to plastic bottles (Mahnot et al., 2014).

Furthermore, two-stage filtrations with low ash filter paper (Whatman 42) and cellulose nitrate membrane of 0.2 μm opening successfully demonstrated the efficacy of membrane filtration in preserving TCW quality (Reddy, Das, & Das, 2007). Nevertheless, nutritional losses were observed in the course of the experiment, which subsequently resulted in low acceptability of the product. Comparable outcomes were documented when TCW had undergone treatment of certain additives along with the process of microfiltration (Mahnot, Gupta,& Mahanta, 2019), where it extended storage life up to 90 days without any undesirable effects. The declining enzyme activity could be attributed to the action of additives, ascorbic, and citric acid, as well as the retention of catalysts by the membrane. Furthermore, the process included 0.8 and 0.45 μm pore size and subsequent addition of ascorbic acid (180 mg/l), citric acid (200 mg/l), and orange honey (5% w/v) even though the latter had barely sufficient ability to destruct the enzymes.

Karmakar and De (2017) explored the feasibility of cold sterilization of TCW using hollow fiber ultrafiltration and found that

Polyacrylonitrile (PAN) of 44 kDa treated with sodium hydroxide act as the filtering membrane with the optimal operating condition of 138 kPa transmembrane (TMP) pressure and 15 l/h cross-flow rate. The resistance-in-series model satisfactorily demonstrated the flux characteristics with a correlation coefficient of 0.99 and 0.98, respectively, for fouling and hydraulic resistance (Karmakar & De, 2017). The model put forward 153–158 kPa as TMP limiting range for Reynolds number 51–152. The transmembrane pressures and Reynolds number strictly affected flux profile, albeit; TMP had a more pronounced effect. Furthermore, shelf-life studies for 18 weeks performed in the sample had only minute changes from fresh coconut water as well, as it had the same organoleptic attributes. Similarly, microfiltered coconut water also seems beneficial in TCW processing (Sumonsiri, 2019). Microfiltration process (Whatman polyether sulfone puradisc syringe filter having a pore size of 0.2 μm and 25 mm diameter) with nisin (25–75 ppm) treatments were conducted by Sumonsiri (2019). Moreover, nisin treatment of 50 ppm provided better samples even after 7 days of storage under refrigerated conditions. The treated TCW had positive marketability along with reduced microbial content.

A kinetic study was conducted by Mahnot, Gupta & Mahanta (2019) in which titratable acidity, free fatty acids, and reducing sugar exhibited zero-order kinetics, whereas total soluble solids, protein content, and antioxidant activity followed the first-order reaction. However, various other models *viz.* Weibull, biphasic and log-linear, and numeric values of fitting curve parameters need to be studied because of their proven performance for various other non-thermal technologies that followed similar inactivation mechanisms. Nonetheless, microfiltration reduced proteins, reducing sugars, total simple sugars by 13.0, 21.5, and 13.4%, respectively, although it did not affect the overall product acceptability from a sensorial point of view (Mahnot, Gupta & Mahanta (2019). Similarly, membrane techniques need to be further explored to find out their feasibility in TCW processing. Compared to the other techniques with high energy expenditure, membrane techniques are more viable if designed and optimized correctly.

2.4. *Ultrasound*

The storage life of TCW declines primarily due to the dark brown and pink discoloration caused by oxidase enzymes. Ultrasound offers to bring about structural changes in the enzymes using any chemical or physical interactions. The mechanisms behind ultrasound action are mechanical and chemical effects of cavitation (Cheng, Zhang, & Adhikari, 2013), as shown in Fig. 2. During the ultrasound application, microbubbles are generated due to fluctuating pressure. The bubbles develop with time, ultimately leading to violent collapse, creating localized high temperature and pressure zones. Similarly, water molecules undergo a sonication process generating highly reactive free radical species. The combined action of both microbubbles and free radicals destroys the secondary and tertiary structure of enzymes (Cheng et al., 2013), ultimately leading to enzyme inactivation. Moreover, these mechanisms influence the three-dimensional conformation of the catalyst proteins (Rojas et al., 2017). However, the processes formulated for TCW using ultrasound are combined techniques such as ozone or thermal processing. This method was followed to cover up the demerits of one technology with the other or increase the easiness of processing. Experiments performed to inactivate peroxidase by sonication suggest the technology as a pre-treatment to thermal processing (Rojas et al., 2017). Application of ultrasound at 286 W/L, 20 kHz, and 25 °C exhibited approximately 27% POD inhibition after 30 min. When compared with other technologies, this amount is barely sufficient, and it could be effective only if high power equipment is utilized. The Weibull model explained the inactivation kinetics of peroxidase in thermally treated as well as in samples pre-treated with ultrasound. The experimental data fitted the model with an R^2 value of 0.97 for both treatments. Furthermore, similar results were acquired in thermosonication applications in coconut water (Ribeiro et al., 2017). The work demonstrated that ultrasound along with mild heat treatments could preserve coconut water without causing much loss to nutritional and sensorial attributes. Moreover, the enzyme activity is strongly correlated with the time of operation and amplitude, where lower amplitude and mild heating may enhance the action of the catalysts (Ribeiro et al., 2017). More than 75% inactivation of PPO and POD was attained during the study with a minimum specific acoustic energy of 500–550 mW/mL. Therefore, thermosonication could be proposed as a favorable approach in the processing of TCW with better retention of nutritional and sensory attributes. Furthermore, the standalone effectiveness of ultrasound also needs to be studied and evaluated for enzymatic, microbial, and qualitative aspects.

2.5. *Ultraviolet*

Different studies have explored the application of ultraviolet (UV) radiation in preserving coconut water. The mechanism under UV radiation follows a conformational change of enzyme structure, as shown in Fig. 3. The underlying enzyme inactivation occurs by a photo-inactivation mechanism involving various unfolding and aggression molecules (Augusto, Ibarz, Garvín, & Ibarz, 2015; Donsingha & Assatarakul, 2018). The photon energy from the UV radiation is absorbed by the enzymes exposing the active sites, which transiently increases enzyme activation, ultimately causing its inactivation. Also, transparency, low-fat content, and less particle content are the major factors affecting UV treatments (Rajashri, Rastogi et al., 2020). In addition, salts and sugars present in the system could expose the interaction sites during molecular unfolding, destabilizing the enzymes (Augusto et al.,

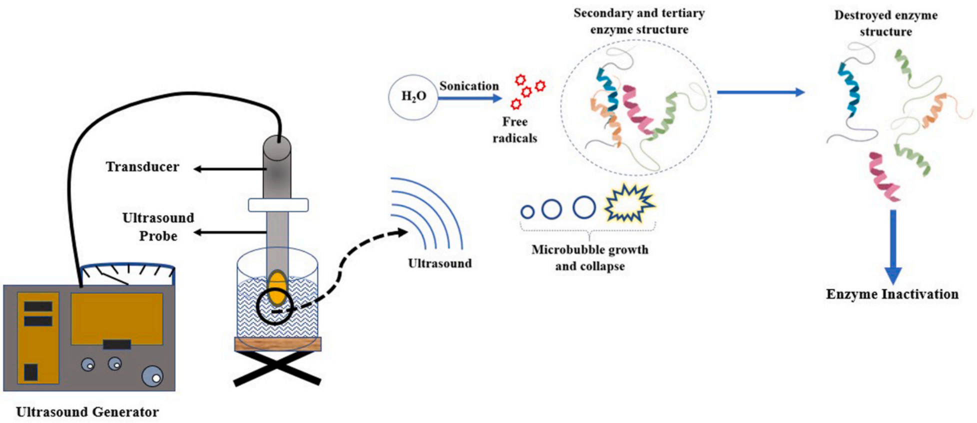

Fig. 2. Enzyme inactivation by ultrasound.

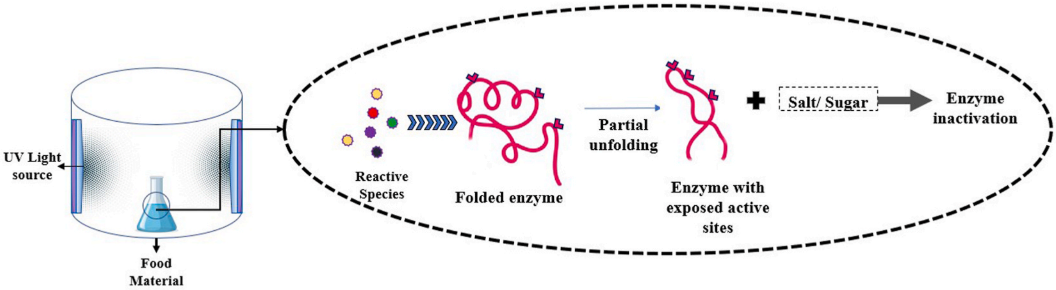

Fig. 3. Enzyme inactivation mechanism of UV treatment.

2015).

Furthermore, a study conducted with a model TCW solution suggests that even at constant UV lamp power, the absorbed power changed after 20 min creating two distinct phases of inactivation and a two-portion model kinetics study for POD (Augusto et al., 2015), which is similar to a biphasic model. Even so, the Weibull model has a good fit with RMSE = 0.06 and $R^2 = 0.97$ (Yannam et al., 2020). Interestingly, microbial inactivation during the UV treatment was following logarithmic-linear first-order kinetics (Gabriel & Colambo, 2016; Gunathunga, Abeywickrema, & Navaratne, 2018) and biphasic for yeast strains (*Kluyveromyces marxianus*, *Trichosporon cutaneum*, *Pichia anomala*, *Meyerozyma guilliermondii*, and *Cryptococcus albidus*) (Feliciano, Estilo, Nakano, & Gabriel, 2019). These models delivered R^2 values greater than 0.9, exhibiting a good fit. However, PPO was inactivated within 5 min, whereas POD inactivation requires 20 min, but hype in absorption spectrum (absorbance vs wavelength plot of absorbed radiation) suggests that overall, PPO was more heat resistant than POD.

An investigation conducted by Yannam et al. (2020) achieved 94 and 93% inactivation of PPO and POD, respectively, using 400 mJ/cm^2 fluence level. This inactivation is sufficient to avoid the pink discoloration caused due to enzymatic browning in TCW. From an application perspective, UV wavelength 255 nm is found to have antimicrobial properties against *Bacillus megatherium, Bacillus subtilis,* and *Bacillus anthracis* with 1.8–18.6 min of exposure time (Augusto et al., 2015). A similar study on pathogenic bacterial resistance of TCW with UV-C dose of 72.80 mJ/cm^2 and 28 s of exposure time found only 28 s needed for 5 log reduction in most resistive cells (Gabriel & Colambo, 2016). The increased dosage achieved D-values under 4 s for *Listeria monocytogenes, Salmonella enterica, Escherichia coli* O157:H7, and *Kluyvera* spp (Gabriel & Colambo, 2016). The decrease in exposure time is due to the former treatment being the combined effect of both high irradiation and exposure areas. Therefore, exposure time, exposure area, and dose of UV radiation have a negative correlation with the microbial load. It is also important to observe that the effect of UV lamp distance and thickness of the sample layer is governed by inverse square law and Lambert-Beer law, respectively, which requires to be optimized and affect various quality parameters are to be studied for better understanding. Also, $D_{UV\text{-}C}$ values depend on UV-C values for specific inactivation runs, therefore regarded as better metrics than D (Feliciano et al., 2019).

For the design and development of equipment, incorporation of stirring mechanism and turbulent behavior was found effective in increasing UV efficiency against certain microbes *viz. S. enterica* (Gabriel & Colambo, 2016), which was further endorsed by the microbial reduction at higher Reynolds number in a dean flow reactor (Gautam et al., 2017). The turbulent flow provides a higher degree of mixing, causing a higher Reynolds number, increasing its antimicrobial properties. Commercially scaled-up studies reported that UV-C doses had great potential for reducing microbial load by 5-log reductions in coconut water (Bhullar, Patras, Kilonzo-Nthenge, Pokharel, & Sasges, 2019). Successfully scaled-up models and proven antimicrobial properties render UV a practically viable technology for both enzyme inactivation and sterilization. Furthermore, the physiochemical attributes of TCW were not significantly affected due to UV treatment (Gautam et al., 2017; Sanganamoni, Purohit, & Rao, 2017; Donsingha & Assatarakul, 2018), especially in pH and TSS. The reduction of acid-producing bacteria and comparatively low settling are found to be the reason for better pH and TSS stabilization, respectively (Gautam et al., 2017). While on the contrary, color and turbidity were affected due to UV treatment. The color difference is a consequence of pigment impairment during irradiation with ΔE values of 3.18 (Gautam et al., 2017). Similar observations were recorded for color values with ΔE between 0.5 and 1.5 (Donsingha & Assatarakul, 2018). Besides, a decrease in yeast and mold had caused a decrease in turbidity (Sanganamoni et al., 2017), increasing the clarity of the coconut water.

On the contrary, Donsingha and Assatarakul (2018) reported stable turbidity levels for UV-treated TCW along with a decrease of phenolic content due to photo-oxidation. From a consumer point of view, a decrease in turbidity, i.e., more clarity, is preferred, but the color change is not desirable. Recent studies have also found out that sensory properties and amino acid composition are not affected by UV treatments (Yannam et al., 2020). Therefore, with minimal quality losses, UV treatments can preserve the natural attributes of TCW. The overall properties of TCW are suitable for UV treatment obtaining good results in the prevention of microbial and enzymatic activity, quality retention, and shelf-life extension. In future storage studies for the UV treatments need to be conducted to understand the preservation and commercial feasibility of TCW processing.

2.6. *Cold plasma*

Cold plasma was studied for microbial and enzyme inactivation of TCW based on the generation of highly reactive gaseous molecules/species. The mechanism behind cold plasma inactivation of enzymes follows the destruction of the second helix and ordered β sheet elements (Misra, Pankaj, Segat, & Ishikawa, 2016), as shown in Fig. 4. The reactive species generated due to plasma react with secondary structures of the enzymes. The unfolded and deformed structures incapacitate enzyme from forming a viable enzyme-substrate complex. This information thus provides critical insight into the composition and their interaction during cold plasma treatments in TCW.

A study conducted by Chutia, Kalita, Mahanta, Ojah, and Choudhury (2019) found a significant reduction in enzyme activity with a marginal temperature rise of only 5 °C using dielectric barrier discharge plasma treatment (DBD) in atmospheric air. This low-temperature treatment could be attributed to the minimal effect on qualitative aspects of TCW. Similar treatment by atmospheric cold plasma generated in air and M65

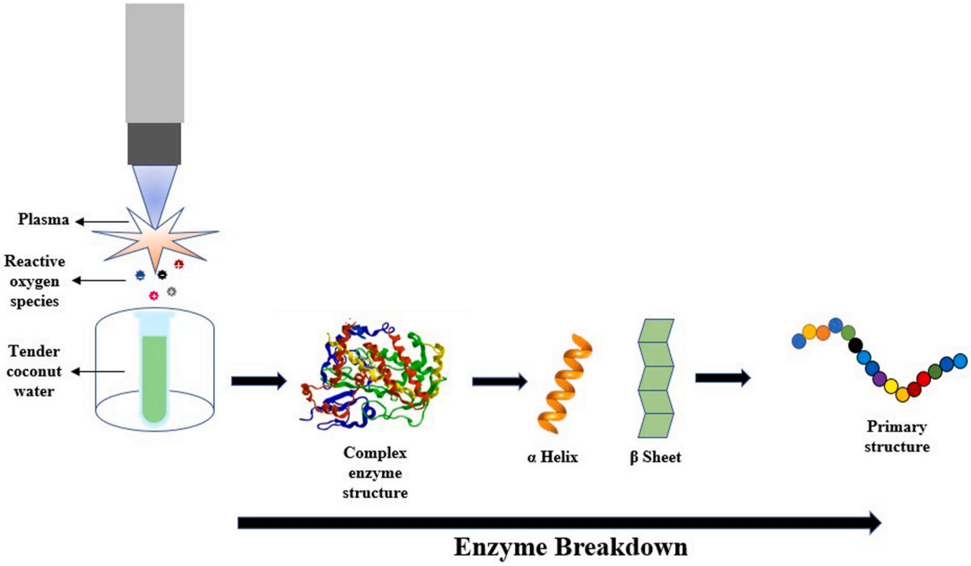

Fig. 4. Mode of action of cold plasma on food enzyme.

(65% O_2, 30% CO_2, 5% N_2) inactivated *Escherinchia coli* and *Listeria monocytogenes* in TCW (Mahnot, Mahanta, Farkas, Keener, &). The cold plasma treatments achieved 5 log reductions as specified by US-FDA guidelines. Cold plasma treatment addresses both the enzymatic and microbial activities, making it one of the effective non-thermal treatments. Moreover, it was found that residual enzymatic activity during cold plasma treatment was predominantly governed by voltage and time ($p \leq 0.05$) (Chutia et al., 2019). Plasma jet process in coconut endosperm targets *Salmonella enterica* as the major target organism in TCW (Gabriel et al., 2016). Since *Salmonella enterica* is the most resistant organism, it can be taken as the indicator of microbial inactivation effectiveness.

Kinetic study of enzymes during cold plasma treatment was compared between first order, Weibull, and logistic model in which the former two were found inadequate due to high RMSE values (Chutia et al., 2019), thereby suggesting a better fit for logistic model. The logistic model with $R^2 > 0.99$ and low RMSE was able to account for POD inactivation's sigmoidal nature, which in turn enabled an excellent fit (Chutia et al., 2019). The cold plasma exposure for 180 s reduced 90% PPO activity whereas, 240 s exposure reduced POD activity to 85% (Chutia et al., 2019) and indicating that POD is more resistant than PPO during cold plasma exposure. In addition, the authors suggest that the underlying mechanism behind the enzyme inactivation could be the same as thermal inactivation.

The bacterial destruction was due to cell collapse and shrinkage during cold plasma exposure, which is aided by nitrous gases and ozone species (Mahnot, Mahanta, Keener, & Misra, 2019). In addition, it was confirmed that rather than acidification, the reactive species played a major role in microbial inactivation (Mahnot, Mahanta, Keener, et al., 2019). These reactive species include molecular species, radicals, and gaseous ions (O_3, H_2O_2, O*, OH*, O^+, O^-) (Pankaj & Keener, 2017). Researchers have previously raised concern about the possibility of plasma induced lipid oxidation (Gavahian, Chu, Khaneghah, Barba, & Misra, 2018; Gavahian, Peng, & Chu, 2019), which necessitate considering this in designing an industrial process.

Investigations on cold plasma treated juices were indicating increased bioaccessibility of bioactive compounds with minimal overall quality loss (de Castro et al., 2020). Also, compared to thermal treatments, the degradation of anthocyanin and vitamin C content was found minimal (Hosseini, Rostami, Hosseinzadeh Samani, & Lorigooini, 2020). Similar studies need to be conducted in TCW to evaluate whether these properties can be achieved for the same. However, the effectiveness of cold plasma in recent years showed promising results in enzymatic and microbial inactivation and minimal quality loss.

2.7. *Pulsed light treatment*

Pulsed light (PL) technology is a non-thermal technique that employs short-duration of high-power light pulses in the broad emission spectrum of 200–1100 nm for inactivation of enzymes and destruction of microorganisms (Kramer & Muranyi, 2014). PL pulses get absorbed in cell DNA, which later interrupts both transcription and translation processes, leading to cell death (Gomez-Lopez, Koutchma, & Linden, 2012) along with photochemical and photophysical effects. PL was very effective for clear liquids such as TCW providing effective *E. coli* destruction characterized by a log reduction of up to 5.33. Similar results are obtained with treatment conditions of 5 mm juice layer height, closest shelf distance of 5 cm from the lamp, and 240 flashes (Preetha, Varadaraju, Kennedy, & Malathi, 2017). The PL fluence rate was also the prime factor governing microbial inactivation (Preetha et al., 2021). The treatment could inactivate various strains and mutants of microorganisms such as *Bacillus subtilis, Geobacillus stearothermophilus*, and its variations (Rajashri, Rastogi et al., 2020). The previous literature also found that transparent foods with thin layer treatment are suitable for PL treatments (Mandal, Mohammadi, Wiktor, Singh, & Singh, 2020), making TCW a suitable material for the same due to its nearly transparent appearance. During the kinetic study, the Weibull model slightly outperformed the log-linear and biphasic models even though all had high R^2 values greater than 0.9 and negligible RMSE values during the PL treatment. The best-fitting models indicate the high predictability of the model during the study and equipment design stages. In addition, quality parameters such as pH, TSS, and color are not affected by the various PL treatment conditions (Preetha et al., 2017). PL treatment in other fruit juices such as pineapple juice preserves most of the quality aspects compared to similar thermal treatments, which had detrimental effects (Vollmer et al., 2020). Similarly, clear juices such as Indian

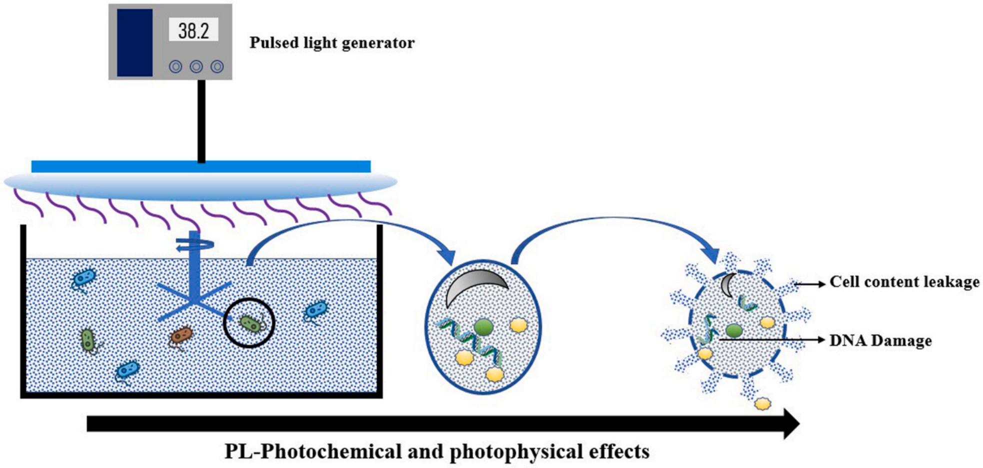

Fig. 5. Photochemical and photophysical mechanism of pulsed light (PL).

gooseberry juice exhibited complete inactivation of PPO and POD enzymes along with maximal quality retention (Chakraborty, Ghag, Bhalerao, & Gokhale, 2020). The properties of tender coconut water are suitable for PL processing; however, a detailed study and process optimization are needed. Also, the technological problems such as PL penetration and treatment homogeneity need to be solved before implementing in a TCW industry.

2.8. *Pulsed electric field treatment*

Compared with other non-thermal processing methods in TCW, the pulsed electric field (PEF) is the most underexplored technology. The method uses a short high voltage electric field and is preferred for liquid products. The antimicrobial effect due to permanent permeabilization of cell membranes is the underlying mechanism behind PEF (Töpfl, 2006), also referred to as electroporation (Fig. 5). The effect of pulsed electric field treatment in TCW for antimicrobial effects was studied by Saraya and Suagatha (2016). The application of square pulses of width 2.5 μs for 6 min with magnitude 35 kV/cm significantly reduces standard plate count (SPC) and destroys *E. coli* (Saraya & Suagatha, 2016). Moreover, the shelf life and sensory evaluation were conducted using pH, acidity, and TSS, which found 18–25 days of shelf life with minimal loss of sensory characters. Therefore, the pulsed electric field is found to be a potential technique for *E. coli* destruction. Studies utilized PEF on other fruit juices that prevented enzymatic browning and ensured quality, sensory attributes, and bioactive compounds (Salehi, 2020). Therefore, these promising approaches in the processing of TCW processing need to be further explored.

3. Combined effects of preservation techniques

We have so far discussed the effects of diverse advanced methodologies in the preservation of TCW. However, most of the techniques considered can provide promising gains when used in conjunction with each other or with thermal processing in a similar way as hurdle technology. Among those synergistic treatments, pressure-assisted thermal processing (PATP) has immense potential in the product stability of TCW (Chourio, Salais-Fierro, Mehmood, Martinez-Monteagudo, & Saldaña, 2018). The authors suggest that 400 MPa pressure at a temperature of 90 °C for 300 s could ensure enzyme inactivation of more than 90%. Moreover, the peroxidase enzyme was more resistant than polyphenol oxidase to the pressure-temperature conditions employed in the experiment. Four different kinetic models were undertaken to study the enzyme inactivation of TCW (first-order, fractional, Weibull, and isozyme). However, fractional and first-order models could not predict the inhibition successfully in accordance with their low values of correlation coefficient (0.839–0.983, 0.375–0.806, respectively). Nevertheless, Weibull and isozyme models exhibited the best fit during the complete study with high R^2 and R^2_{adj} values. This method prevented the formation of pink color, and no traces of enzymes were found after the prescribed optimal parameters. Higher residual activity of both the catalysts at a lower temperature of 40 °C and high pressure in the range of 200–600 MPa was substantiated by the limited structural rearrangements of the catalysts. Hence it could be considered as an emerging technology that can help in the preservation of coconut water.

Acoustic field-assisted ultrafiltration is employed to gain insight into the enzyme retardation of TCW besides ultrafiltration (Lamdande et al., 2020). Samples were analyzed at four different pressures of 1, 2, 3, and 4.5 bar and polyethersulfone membrane with 30 and 100 kDa accompanied by an acoustic field of 1.2 MHz (Lamdande et al., 2020). Results revealed that 95.10% and 97.89% of PPO and POD were destructed, and 95.81% turbidity was reduced by the ultrafiltration technique alone, whereas in the combination procedure, the outcomes were insignificant (Lamdande et al., 2020). Furthermore, the filtered TCW, even after three months of storage, presented positive results in overall product acceptability. Contrarily, in an experiment on cold plasma treatment of TCW, the samples developed a chemical odor at the optimized operating conditions (Chutia, Mahanta, Ojah, & Choudhury, 2020). The development of such a remarkable abnormality created unfavorable sensory scores. This indifference could be concealed by blending cold plasma treated TCW with 1–4% orange juice (Chutia et al., 2020). Hence, to acquire a better product with higher overall acceptance, fuzzy logic studies reveal that cold plasma parameters of 18 kV voltage and 1.75 min exposure time and the addition of 1% orange juice are optimal. The experimental data of TCW well fitted into quadratic model having high values of R^2 (transmittance- 0.97, DPPH scavenging- 0.95, microbial load- 0.99, free fatty acids-0.98).

4. Industrialization of emerging techniques for TCW

The pros and cons of emerging technologies are highlighted in Table 2. The fruit juice industries are started adopting HPP on a commercial scale. Nevertheless, limited throughput and high capital expenditure are the main limitations of this technology for fruit juice processing. The orange juice pasteurization cost of HPP is 7 folds higher than the thermal pasteurization method (Sampedro, McAloon, Yee, Fan, & Geveke, 2014). However, the HPP treatment retains the product's flavor, sensory and nutritional profile than the conventional pasteurization method. The effect of processing parameters of microfiltration, ultraviolet, and pulsed light treatments on the nutritional and sensory

Table 2
Advantages and disadvantages of different non-thermal technologies associated with tender coconut water (TCW) processing.

Technology	Advantages	Disadvantages	Precautions	References
Ozone	Onsite generation and has GRAS status Destroyed microbial count Reduced enzyme activities Treated TCW had acceptable sensory score No deleterious effect on TSS of TCW Maintained the colour of fresh TCW as well as its other quality parameters (0.075–0.37 mg/mL) Saves the requirement of energy inputs	Caused changes in pH and acidity of TCW Reduced total solids, total phenolics and Ascorbic acid content Corrosive at high concentrations Inhaling of ozone may result in breathing problems Regular supervision is needed to check on leakages	The US Federal Occupational Safety and Health Administration has set a limit of 0.1 ppm threshold for continuous 8-h exposure and 0.3 ppm for 15 min to reduce its detrimental health effects.	(Porto et al., 2020; Prabha, Barma, Singh, & Madan, 2015; Rajashri, Roopa et al., 2020; Taylor, Karaca, & Velioglu, 2007)
HPP	Ensures microbial safety Caused no changes in pH, TSS, and TA values of product No significant losses in total amino acids, proteins, sugars etc (500 MPa, 5 min) Exhibited the characteristics similar to that of fresh CW Waste-free process and reduces environmental pollution	Slightly decreased the lightness of CW (500 MPa, 5 min) High capital investment is required for equipment	Suitable pressure conditions should be applied to product as inappropriate values may retain microorganisms and enzymes In order to product quality, it should be conveyed at low temperature.	(Ma et al., 2019; Raghubeer et al., 2020; Wang, Huang, Hsu, & Yang, 2016)
Filtration	Significantly retardation microbial count Treated TCW showed negligible deviation from its initial value of quality parameters Helps to maintain a stable pH Reduces undesirable enzyme activities Easy to use and implement and also reduces risk of contamination	Microfiltered TCW samples (0.8 μm and 0.45 μm pore size) showed a reduction in its nutritional components Fouling of the membrane reduce the efficiency of process Membrane fouling results in high maintenance and reduced flux	Regular cleaning of membrane is necessary to restore fouled membranes which otherwise reduce the efficacy of the procedure. To prevent penetration of fouling agents deeply, pressure applied in cleaning process should be lower than those employed for filtration	(Karmakar & De, 2017; Mahnot, Gupta, et al., 2019; Mohammad, Ng, Lim, & Ng, 2012)
Ultrasound	Inactivation of enzymes Combination with heat treatments (thermosonication) results in lesser processing time Enhance food quality at lower temperatures Reduce pathogenic microorganisms Flavour loss is minimum Enzyme inactivation to undetectable levels is possible when used synergistically with heat	High equipment cost High power equipment is needed for maximum inactivation of enzymes and microorganisms	Metal contamination from ultrasound horn	(Chemat, Zill-E-Huma, & Khan, 2011; Ribeiro et al., 2017)
Ultraviolet	Low initial investment and less maintenance Retains the quality attributes of food product Environment friendly May be combined with other technologies to get more pronounced effects Inactivation spoilage causing microorganisms and undesirable enzymes along with retention of essential amino acids in TCW	Exposure for long durations could damage eyes, skin etc Difficult to predict the rate of disinfection Low penetration power in foods	Radiation sources should consist of low-pressure mercury lamps The lamps should emit 90% light wavelength of 253.7 nm (2537 Å).	(CFR, n.d.; Delorme et al., 2020; Yannam et al., 2020)
Cold Plasma Technology	Reduced spoilage microorganisms in TCW The treatment had minimal effects on the quality parameters of TCW Caused a decline in the rate of spoilage enzymes (PPO, POD) Chemical free technology which is waterless, rapid and of zero-contact	May cause discoloration of products Can cause an increase in acidity of food Change in pH value of TCW after the treatment with plasma technique Lower penetration depth	Oxidation reactions needs to taken care by selecting appropriate carrier gas and antioxidant compounds	(Chizoba Ekezie, Sun, & Cheng, 2017; Mahnot, Mahanta, Farkas, et al., 2019; Mahnot, Mahanta, Keener, et al., 2019)
Pulsed Electric Field	Efficient in the destruction of pathogenic microbial cells Lesser time for processing Retain most of the quality parameters	Capital cost is high Bubbles in the product may lead to inefficient treatment and other problems	Treatment chamber should have cleaning and unclogging systems Safety measures like shield or interlocks should be there to cover treatment chambers and equipment Excluded zones should be well protected with fences or interlocks	(Bhat et al., 2018; Kempkes, 2016; Saraya & Suagatha, 2016)
Pulsed light	Do not leave any toxic residues Efficient and faster method of disinfection Operational cost is less	Initial investments are high Lamps used may have shorter life time Can cause over-heating of samples	Proper reflector positioning Check working of air/water cooling system	(Mahendran et al., 2019; Preetha et al., 2017)

TCW-Tender Coconut Water; GRAS-Generally Recognized as Safe; PPO-Polyphenol oxidase; POD- Peroxidase.

qualities of TCW has been extensively studied, and the engineering aspects of these technologies have progressed toward its commercial-scale adoption. Also, a combination of UV-C treatments with heat treatments is found to obtain extended shelf life at low-temperature storages (Gunathunga et al., 2018). The influence of ozone, cold plasma, ultrasound, and pulsed electric field on functional constituents of TCW may require further understanding and refinement in its equipment for industrial-scale is essential for commercial adoption. However, these technologies offer ample scope for improving the enzymatic and microbial quality of TCW with minimal impact on sensory attributes. The large-scale pulsed electric field treatment system (30 kV/cm and 60 °C) designed for pasteurization of orange juice is 147% costlier than the conventional pasteurization system (Sampedro et al., 2013). The cost of a pulsed electric field treatment system may come down with technology innovation and broader industrial adaptation. Also, knowledge of the processing cost is essential to understand the pros and cons of the pulsed electric field treatment system. Lee et al. (2021) developed a large-scale Plasma Jet-Pulsed Light-Ultraviolet-C integrated system for microbial decontamination of particulate foods. They concluded that the combined treatments are more effective than individual treatments. Similarly, the TCW industries are looking for a large-scale integrated system (hybrid and/or combined technology) for shelf life extension.

5. Conclusion and future directions

TCW is a high potential electrolytic natural drink. However, relatively stable microbial and enzyme activity are a significant challenge in preservation and shelf-life extension. Nevertheless, the shift of consumers' preference for more natural and organic products had increased the market potential of TCW. Although thermal processing techniques are explored due to their inherent limitations and detrimental effects on sensory attributes, non-thermal technologies are being investigated. These include high-pressure processing, cold plasma, filtration, ozone technology, pulsed light, pulsed electric field, ultrasound, and ultraviolet treatments. Almost all the reviewed techniques were able to significantly depreciate enzyme activity significantly and thus ensured an extended shelf life. Recent studies had shown that along with antimicrobial and enzyme inactivation. These techniques preserve most of the sensory properties. Even a combination of these techniques and thermal treatments provides a synergic effect for obtaining a better product. Furthermore, the underlying mechanism of these technologies needs to be examined, and commercially viable techniques need to be created for industrial-scale applications based on the techno-economical aspects.

CRediT authorship contribution statement

V. Prithviraj: Project administration, Literature searching & Writing – original draft. **R. Pandiselvam:** Project administration, Literature searching & Writing – original draft. **Ardra C. Babu:** Project administration, Literature searching & Writing - original draft. **Anjineyulu Kothakota:** Project administration, Literature searching & Writing – original draft. **M.R. Manikantan:** Project administration, Literature searching & Writing – original draft. **S.V. Ramesh:** Project administration, Literature searching. **P.P. Shameena Beegum:** Conceptualization, Writing – review & editing. **A.C. Mathew:** Writing – review & editing, Supervision. **K.B. Hebbar:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2021.111850.

References

Aniesrani Delfiya, D. S., & Thangavel, K. (2016). Effect of ohmic heating on polyphenol oxidase activity, electrical and physicochemical properties of fresh tender coconut water. *International Journal of Food Engineering, 12*(7), 691–700. https://doi.org/10.1515/ijfe-2015-0329

Augusto, P. E. D., Ibarz, R., Garvín, A., & Ibarz, A. (2015). Peroxidase (POD) and polyphenol oxidase (PPO) photo-inactivation in a coconut water model solution using ultraviolet (UV). *Food Research International, 74*, 151–159. https://doi.org/10.1016/j.foodres.2015.04.046

Bhat, Z. F., Morton, J. D., et al.Bhat, Z. F., Morton, J. D., Mason, S. L., & Bekhit, A. E. A. (2018). Current and future prospects for the use of pulsed electric field in the meat industry. *Critical Reviews in Food Science and Nutrition*, 8398. https://doi.org/10.1080/10408398.2018.1425825

Bhullar, M. S., Patras, A., Kilonzo-Nthenge, A., Pokharel, B., & Sasges, M. (2019). Ultraviolet inactivation of bacteria and model viruses in coconut water using a collimated beam system. *Food Science and Technology International, 25*(7), 562–572. https://doi.org/10.1177/1082013219843395

Cappelletti, M., Ferrentino, G., Endrizzi, I., Aprea, E., Betta, E., Corollaro, M., et al. (2015). High pressure carbon dioxide pasteurization of coconut water: A sport drink with high nutritional and sensory quality. *Journal of Food Engineering, 145*, 73–81. https://doi.org/10.1016/j.jfoodeng.2014.08.012

CDB - Statistics. (2018). https://www.coconutboard.gov.in/Statistics.aspx. (Accessed 24 December 2020).

CFR. (2020). *CFR - code of federal regulations title 21*. http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=50.25.

Chakraborty, S., Ghag, S., Bhalerao, P. P., & Gokhale, J. S. (2020). The potential of pulsed light treatment to produce enzymatically stable Indian gooseberry (Emblica officinalis Gaertn.) juice with maximal retention in total phenolics and vitamin C. *Journal of Food Processing and Preservation, 44*(12), 1–12. https://doi.org/10.1111/jfpp.14932

Chakraborty, S., Kaushik, N., Rao, P. S., & Mishra, H. N. (2014). High-pressure inactivation of enzymes: A review on its recent applications on fruit purees and juices. *Comprehensive Reviews in Food Science and Food Safety, 13*(4), 578–596. https://doi.org/10.1111/1541-4337.12071

Chemat, F., Zill-E-Huma, & Khan, M. K. (2011). Applications of ultrasound in food technology: Processing, preservation and extraction. *Ultrasonics Sonochemistry, 18*(4), 813–835. https://doi.org/10.1016/j.ultsonch.2010.11.023

Cheng, X. F., Zhang, M., & Adhikari, B. (2013). The inactivation kinetics of polyphenol oxidase in mushroom (Agaricus bisporus) during thermal and thermosonic treatments. *Ultrasonics Sonochemistry, 20*(2), 674–679. https://doi.org/10.1016/j.ultsonch.2012.09.012

Chizoba Ekezie, F. G., Sun, D. W., & Cheng, J. H. (2017). A review on recent advances in cold plasma technology for the food industry: Current applications and future trends. *Trends in Food Science & Technology, 69*, 46–58. https://doi.org/10.1016/j.tifs.2017.08.007

Chourio, A. M., Salais-Fierro, F., Mehmood, Z., Martinez-Monteagudo, S. I., & Saldaña, M. D. (2018). Inactivation of peroxidase and polyphenoloxidase in coconut water using pressure-assisted thermal processing. *Innovative Food Science & Emerging Technologies, 49*, 41–50. https://doi.org/10.1016/j.ifset.2018.07.014

Chutia, H., Kalita, D., Mahanta, C. L., Ojah, N., & Choudhury, A. J. (2019). Kinetics of inactivation of peroxidase and polyphenol oxidase in tender coconut water by dielectric barrier discharge plasma. *Lebensmittel-Wissenschaft & Technologie, 101*, 625–629. https://doi.org/10.1016/j.lwt.2018.11.071

Chutia, H., Mahanta, C. L., Ojah, N., & Choudhury, A. J. (2020). Fuzzy logic approach for optimization of blended beverage of cold plasma treated TCW and orange juice. *Journal of Food Measurement and Characterization, 14*(4), 1926–1938. https://doi.org/10.1007/s11694-020-00440-1

Das Purkayastha, M., Kalita, D., Mahnot, N. K., Mahanta, C. L., Mandal, M., & Chaudhuri, M. K. (2012). Effect of l-ascorbic acid addition on the quality attributes of micro-filtered coconut water stored at 4°C. *Innovative Food Science & Emerging Technologies, 16*, 69–79. https://doi.org/10.1016/j.ifset.2012.04.007

Delorme, M. M., Guimarães, J. T., Coutinho, N. M., Balthazar, C. F., Rocha, R. S., Silva, R., et al. (2020). Ultraviolet radiation: An interesting technology to preserve quality and safety of milk and dairy foods. *Trends in Food Science and Technology; Elsevier*. https://doi.org/10.1016/j.tifs.2020.06.001

Donsingha, S., & Assatarakul, K. (2018). Kinetics model of microbial degradation by UV radiation and shelf life of coconut water. *Food Control, 92*, 162–168. https://doi.org/10.1016/j.foodcont.2018.04.030

Dwiloka, B., Rizqiati, H., & Setiani, B. E. (2020). Physicochemical and sensory characteristics of green coconut (Cocos nucifera L.) water kefir. *International Journal of Food Studies, 9*(2), 346–359. https://doi.org/10.7455/ijfs/9.2.2020.a7

Edison, E., & Ann, I. M. (2018). *'Cocos Nucifera Water : Therapeutic Benefits and Sickle Cell Anaemiaa Review', 3*(8), 514–520.

Feliciano, R. J., Estilo, E. E. C., Nakano, H., & Gabriel, A. A. (2019). Decimal reduction energies of UV-C-irradiated spoilage yeasts in coconut liquid endosperm. *International Journal of Food Microbiology, 290*, 170–179. https://doi.org/10.1016/j.ijfoodmicro.2018.10.012

Gabriel, A. A., & Colambo, J. C. R. (2016). Comparative resistances of selected spoilage and pathogenic bacteria in ultraviolet-C-treated, turbulent-flowing young coconut liquid endosperm. *Food Control, 69*, 134–140. https://doi.org/10.1016/j.foodcont.2016.04.046

Gautam, D., Umagiliyage, A. L., Dhital, R., Joshi, P., Watson, D. G., Fisher, D. J., et al. (2017). Non-thermal pasteurization of tender coconut water using a continuous flow coiled UV reactor. *LWT-Food Science and Technology, 83*, 127–131. https://doi.org/10.1016/j.lwt.2017.05.008

Gavahian, M., Chu, Y. H., Khaneghah, A. M., Barba, F. J., & Misra, N. N. (2018). A critical analysis of the cold plasma induced lipid oxidation in foods. *Trends in Food Science & Technology, 77*, 32–41.

Gavahian, M., Peng, H. J., & Chu, Y. H. (2019). Efficacy of cold plasma in producing salmonella-free duck eggs: Effects on physical characteristics, lipid oxidation, and fatty acid profile. *Journal of Food Science & Technology, 56*(12), 5271–5281.

Gómez-López, V., Koutchma, T., & Linden, K. (2012). Ultraviolet and pulsed light processing of fluid foods. *Novel Thermal and Non-Thermal Technologies for Fluid Foods*, 185–223. https://doi.org/10.1016/B978-0-12-381470-8.00008-6

Gunathunga, C., Abeywickrema, S., & Navaratne, S. (2018). *Preservation of tender coconut (Cocos nucifera L .) water by heat and UV-C treatments* (pp. 15–19). May http://dr.lib.sjp.ac.lk/handle/123456789/8801.

Jaramillo Sánchez, G. M., Garcia Loredo, A. B., Contigiani, E. V., Gómez, P. L., & Alzamora, S. M. (2018). Inactivation kinetics of peroxidase and polyphenol oxidase in peach juice treated with gaseous ozone. *International Journal of Food Science and Technology, 53*(2), 347–355. https://doi.org/10.1111/ijfs.13591

Karmakar, S., & De, S. (2017). Cold sterilization and process modeling of tender coconut water by hollow fibers. *Journal of Food Engineering, 200*, 70–80. https://doi.org/10.1016/j.jfoodeng.2016.12.021

Kempkes, M. A. (2016). *Handbook of electroporation. Handbook of electroporation*. https://doi.org/10.1007/978-3-319-26779-1. April.

Kramer, B., & Muranyi, P. (2014). Effect of pulsed light on structural and physiological properties of Listeria innocua and Escherichia coli. *Journal of Applied Microbiology, 116*(3), 596–611. https://doi.org/10.1111/jam.12394

Lamdande, A. G., Mittal, R., & Raghavarao, K. S. M. S. (2020). Flux evaluation based on fouling mechanism in acoustic field-assisted ultrafiltration for cold sterilization of tender coconut water. *Innovative Food Science & Emerging Technologies, 61*, Article 102312. https://doi.org/10.1016/j.ifset.2020.102312

Lee, S. Y., Lee, W. K., Lee, J. W., Chung, M., Oh, S., Shin, J., et al. (2021). Microbial decontamination of rice germ using a large-scale plasma jet-pulsed light-ultraviolet-C integrated treatment system. *Food and Bioprocess Technology*. https://doi.org/10.1007/s11947-021-02590-6. Accepted.

Mahendran, R., Ramanan, K. R., Barba, F. J., Lorenzo, J. M., López-fernández, O., Munekata, P. E. S., et al. (2019). Trends in Food Science & Technology Recent advances in the application of pulsed light processing for improving food safety and increasing shelf life. *Trends in Food Science & Technology, 88*(March), 67–79. https://doi.org/10.1016/j.tifs.2019.03.010

Mahnot, N. K., Gupta, K., & Mahanta, C. L. (2019c). Shelf life enhancement and associated quality and sensory changes on refrigerated storage of tender coconut water subjected to non-thermal microfiltration and treated with additives. *Journal of Food Science and Technology, 56*(7), 3408–3421. https://doi.org/10.1007/s13197-019-03825-3

Mahnot, N. K., Kalita, D., Mahanta, C. L., & Chaudhuri, M. K. (2014). Effect of additives on the quality of tender coconut water processed by non-thermal two stage microfiltration technique. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 59*(2P1), 1191–1195. https://doi.org/10.1016/j.lwt.2014.06.040

Mahnot, N. K., Mahanta, C. L., Farkas, B. E., Keener, K. M., & Misra, N. N. (2019a). Atmospheric cold plasma inactivation of Escherichia coli and Listeria monocytogenes in tender coconut water: Inoculation and accelerated shelf-life studies. *Food Control, 106*, Article 106678. https://doi.org/10.1016/j.foodcont.2019.06.004

Mahnot, N. K., Mahanta, C. L., Keener, K. M., & Misra, N. N. (2019b). Strategy to achieve a 5-log Salmonella inactivation in tender coconut water using high voltage atmospheric cold plasma (HVACP). *Food Chemistry, 284*, 303–311. https://doi.org/10.1016/j.foodchem.2019.01.084

Ma, Y., Xu, L., Wang, S., Xu, Z., Liao, X., & Cheng, Y. (2019). Comparison of the quality attributes of coconut waters by high-pressure processing and high-temperature short time during the refrigerated storage. *Food Sciences and Nutrition, 7*(4), 1512–1519. https://doi.org/10.1002/fsn3.997

Misra, N. N., Pankaj, S. K., Segat, A., & Ishikawa, K. (2016). Cold plasma interactions with enzymes in foods and model systems. *Trends in Food Science & Technology, 55*, 39–47. https://doi.org/10.1016/j.tifs.2016.07.001

Mohammad, A. W., Ng, C. Y., Lim, Y. P., & Ng, G. H. (2012). Ultrafiltration in food processing industry: Review on application, membrane fouling, and fouling control. *Food and Bioprocess Technology, 5*(4), 1143–1156. https://doi.org/10.1007/s11947-012-0806-9

Naik, M., CK, S., & Rawson, A. (2020). Tender coconut water: A review on recent advances in processing and preservation. *Food Reviews International*, 1–22. https://doi.org/10.1080/87559129.2020.1785489

Ochoa-Velasco, C. E., Díaz-Lima, M. C., Ávila-Sosa, R., Ruiz-López, I. I., Corona-Jiménez, E., Hernández-Carranza, P., & Guerrero-Beltrán, J. A. (2018). Effect of UV-C light on Lactobacillus rhamnosus, Salmonella Typhimurium, and Saccharomyces cerevisiae kinetics in inoculated coconut water: Survival and residual effect. *Journal of Food Engineering, 223*, 255–261. https://doi.org/10.1016/j.jfoodeng.2017.10.010

Pandiselvam, R., Kaavya, R., Jayanath, Y., Veenuttranon, K., Lueprasitsakul, P., Divya, V., & Ramesh, S. V. (2020). Ozone as a novel emerging technology for the dissipation of pesticide residues in foods–a review. *Trends in Food Science & Technology, 97*, 38–54.

Pandiselvam, R., Subhashini, S., Banuu Priya, E. P., Kothakota, A., Ramesh, S. V., & Shahir, S. (2019). Ozone based food preservation: A promising green technology for enhanced food safety. *Ozone: Science & Engineering, 41*(1), 17–34.

Pandiselvam, R., Sunoj, S., Manikantan, M. R., Kothakota, A., & Hebbar, K. B. (2017). Application and kinetics of ozone in food preservation. *Ozone: Science & Engineering, 39*(2), 115–126.

Pankaj, S. K., & Keener, K. M. (2017). Cold plasma: Background, applications and current trends. *Current Opinion in Food Science, 16*, 49–52. https://doi.org/10.1016/j.cofs.2017.07.008

Picart-Palmade, L., Cunault, C., Chevalier-Lucia, D., Belleville, M. P., & Marchesseau, S. (2019). Potentialities and limits of some non-thermal technologies to improve sustainability of food processing. *Frontiers in Nutrition, 5*, 130. https://doi.org/10.3389/fnut.2018.00130

Porto, E., Alves Filho, E. G., Silva, L. M. A., Fonteles, T. V., do Nascimento, R. B. R., Fernandes, F. A., … Rodrigues, S. (2020). Ozone and plasma processing effect on green coconut water. *Food Research International, 131*, Article 109000. https://doi.org/10.1016/j.foodres.2020.109000

Prabha, V., Barma, R. D. E. B., Singh, R., & Madan, A. (2015). Ozone technology in. *Food Processing: A Review, 8*(16), 4031–4047.

Preetha, P., Pandiselvam, R., Varadharaju, N., Kennedy, Z. J., Balakrishnan, M., & Kothakota, A. (2020). Effect of pulsed light treatment on inactivation kinetics of Escherichia coli (MTCC 433) in fruit juices. *Food Control, 121*, Article 107547. https://doi.org/10.1016/j.foodcont.2020.107547

Preetha, P., Varadaraju, N., Kennedy, J., & Malathi, D. (2017). Modelling for the survival of Escherichia coli in tender coconut (cocos nucifera l.) water by non-thermal pulsed light treatment. *Madras Agricultural Journal, 104*(4–6), 1453–1461. https://doi.org/10.29321/maj.04.000431

Raghubeer, E. V., Phan, B. N., Onuoha, E., Diggins, S., Aguilar, V., Swanson, S., et al. (2020). The use of High-Pressure Processing (HPP) to improve the safety and quality of raw coconut (Cocos nucifera L) water. *International Journal of Food Microbiology*. https://doi.org/10.1016/j.ijfoodmicro.2020.108697, 108697.

Rajashri, K., Rastogi, N. K., & Negi, P. S. (2020b). *'Non- thermal processing of tender coconut water - a review.', food reviews International* (pp. 1–22). Taylor & Francis. https://doi.org/10.1080/87559129.2020.1847142, 00(00).

Rajashri, K., Roopa, B. S., Negi, P. S., & Rastogi, N. K. (2020a). Effect of ozone and ultrasound treatments on polyphenol content, browning enzyme activities, and shelf life of tender coconut water. *Journal of Food Processing and Preservation, 44*(3), Article e14363. https://doi.org/10.1111/jfpp.14363

Reddy, K. V., Das, M., & Das, S. K. (2007). Non-thermal sterilization of green coconut water for packaging. *Journal of Food Quality, 30*(4), 466–480. https://doi.org/10.1111/j.1745-4557.2007.00136.x

Ribeiro, M. de M., Valdramidis, V. P., Nunes, C. A., & de Souza, V. R. (2017). Synergistic effect of thermosonication to reduce enzymatic activity in coconut water. *Innovative Food Science & Emerging Technologies, 41*, 404–410. https://doi.org/10.1016/j.ifset.2017.04.013

Rojas, M. L., Trevilin, J. H., dos Santos Funcia, E., Gut, J. A. W., & Augusto, P. E. D. (2017). Using ultrasound technology for the inactivation and thermal sensitization of peroxidase in green coconut water. *Ultrasonics Sonochemistry, 36*, 173–181. https://doi.org/10.1016/j.ultsonch.2016.11.028

Salehi, F. (2020). Physico-chemical properties of fruit and vegetable juices as affected by pulsed electric field: A review. *International Journal of Food Properties, 23*(1), 1036–1050. https://doi.org/10.1080/10942912.2020.1775250

Sampedro, F., McAloon, A., Yee, W., Fan, X., & Geveke, D. J. (2014). Cost analysis and environmental impact of pulsed electric fields and high pressure processing in comparison with thermal pasteurization. *Food and Bioprocess Technology, 7*(7), 1928–1937.

Sampedro, F., McAloon, A., Yee, W., Fan, X., Zhang, H. Q., & Geveke, D. J. (2013). Cost analysis of commercial pasteurization of orange juice by pulsed electric fields. *Innovative Food Science & Emerging Technologies, 17*, 72–78.

Sanganamoni, S., Purohit, S., & Rao, P. S. (2017). Effect of ultraviolet-C treatment on enzymes and nutritional properties of tender coconut water. *International Journal of*

Current Microbiology and Applied Sciences, 6(5), 2905–2918. https://doi.org/10.20546/ijcmas.2017.605.330

Saraya, S., & Suagatha, G. (2016). Preservation of tender coconut water using pulsed electric field. *International Journal of Agricultural Science and Research (IJASR), 6*(4), 251–256.

Sobrino-López, A., & Martín-Belloso, O. (2008). Use of nisin and other bacteriocins for preservation of dairy products. *International Dairy Journal, 18*(4), 329–343. https://doi.org/10.1016/j.idairyj.2007.11.009

Sumonsiri, N. (2019). Effect of nisin on microbial, physical and sensory qualities of micro-filtered coconut water (cocos nucifera L.) during refrigerated storage. *Current Research in Nutrition and Food Science, 7*(1), 236–243. https://doi.org/10.12944/CRNFSJ.7.1.23

Taylor, P., Karaca, H., & Velioglu, Y. S. (2007). *Ozone applications in fruit and vegetable processing ozone applications in fruit and.* https://doi.org/10.1080/87559120600998221. April 2013, 37–41.

Tetra Pack. (2019). *The coconut Handbook: Technology, engineering. Agriculture* (pp. 1–183). Tetra Pak International SA.

Töpfl, S. (2006). *Pulsed electric fields (PEF) for permeabilization of cell membranes in food- and bioprocessing. Applications, process and equipment design and cost analysis* (pp. 128–130). Technological University of Berlin. https://doi.org/10.14279/depositonce-1441. April.

Vardharaju, H. T. N., & Chandrasekar, V. (2016). *Influence of Ozonation on the Some Physicochemical Properties of, 5*(10), 4153–4159.

Vollmer, K., Chakraborty, S., Bhalerao, P. P., Carle, R., Frank, J., & Steingass, C. B. (2020). Effect of pulsed light treatment on natural microbiota, enzyme activity, and phytochemical composition of pineapple (ananas comosus [L.] merr.) juice. *Food and Bioprocess Technology, 13*(7), 1095–1109. https://doi.org/10.1007/s11947-020-02460

Wang, C. Y., Huang, H. W., Hsu, C. P., & Yang, B. B. (2016). Recent advances in food processing using high hydrostatic pressure technology. *Critical Reviews in Food Science and Nutrition, 56*(4), 527–540. https://doi.org/10.1080/10408398.2012.745479

Woldemariam, H. W., & Emire, S. A. (2019). High pressure processing of foods for microbial and mycotoxins control: Current trends and future prospects. *Cogent Food & Agriculture. Cogent, 5*(1). https://doi.org/10.1080/23311932.2019.1622184

Yannam, S. K., Patras, A., Pendyala, B., Vergne, M., Ravi, R., Gopisetty, V. V. S., et al. (2020). Effect of UV-C irradiation on the inactivation kinetics of oxidative enzymes, essential amino acids and sensory properties of coconut water. *Journal of Food Science & Technology, 57*(10), 3564–3572. https://doi.org/10.1007/s13197-020-04388-4. https://www.webmd.com/vitamins/ai/ingredientmono-1261/coconut-water. (Accessed 27 May 2021)