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REVIEW

Hurdle Technologies Using Ultraviolet Irradiation as Preservation Strategies in Fruit Juices: Effects on Microbial, Physicochemical, and Sensorial Qualities

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Abstract

Non-thermal processes are employed to decontaminate juice products with less negative impact on biochemical, sensorial, and nutritional properties of the products compared with traditional thermal processing. Different non-thermal technologies have been investigated to improve the quality and/or avoid undesirable changes in fruit juices that include ultraviolet (UV) irradiation, pulsed electric field (PEF), ultrasonication, ozonation, high-pressure processing, and membrane filtration. In this review, which focuses on current studies, largely from a decade ago, the combined impacts of UV irradiation and other non-thermal technologies (hurdle concept) on fresh fruit juices are addressed. The extensively researched products regarding the application of UV light processing to improve safety, maintain overall quality, and prolong shelf life were apple and orange juices. Based on the studies reviewed, the hurdle techniques (e.g., UV + PEF, UV + mild heat at 50 °C, UV-C + coupled microwave, UV + ultrasonication) reduced (> 5 log) spoilage/pathogenic microbes, viruses, and inactivated enzymes, while maintaining the fresh-like nutritional and sensorial quality of juices. However, achieving the right balance and synergy in hurdle technologies can be a challenge which should be more addressed in the future studies. Human trials also indicated that UV-irradiated juice had no cytotoxic effects on normal intestinal cells, but it stopped human colon cancer cells from growing. Treating fruit juices with UV in combination with other non-thermal hurdles could be an alternative to traditional thermal processing technologies in the food industry. However, commercialization, scale-up, regulatory, safety, economic, and ethical concerns of these technologies should be taken into consideration.

Keywords Fruit juice · Hurdle technology · Preservation · Shelf-life extension · UV irradiation

Introduction

Fruit juices are a vital component of a healthy diet due to their substantial phytochemical constituents that contribute to nutritional and health-promoting effects in consumers (Khandpur & Gogate, 2015). However, the release of these phytochemicals from the fruit into the juice could be affected during uncontrolled processing conditions and subsequent improper storage conditions. For example, during improper processing and storage of fresh juices, a degradation of phenolics, flavonoids, ascorbic acid, proteins, and fatty acids takes place once the cellular protection of these compounds is no longer present after extraction. The activity of polyphenol oxidase triggers browning reactions that are enhanced by temperature, pH, and storage environment normally used in food processing and storage (Antonio-Gutiérrez et al., 2017). Several types of microorganisms can spoil fruit juice, including bacteria (e.g., *Lactobacillus* spp., *Leuconostoc* spp., *Pediococcus*

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spp., and *Acetobacter* spp.), yeast (e.g., *Candida* spp., *Hanseniaspora* spp. and *Zygosaccharomyces* spp.) and, mold (*Aspergillus* spp., *Penicillium* spp. and *Cladosporium* spp.) which compromise the safety and deteriorate the quality of fruit juices during storage (Pinto et al., 2022).

Conventional thermal pasteurization and sterilization technologies have been used as the standard practice to inactivate enzymes and microorganisms that compromise the safety of fruit juices. However, the thermal processing of fruit juices has been reported to affect the nutritional, physicochemical, and sensory properties of the products due to changes in color, flavor, vitamins, and volatile sensory components, as well as protein denaturation (Khandpur & Gogate, 2015). Furthermore, it has been documented that thermal processing methods (e.g., pasteurization, blanching, and ohmic heating) may activate dormant ascospores of molds in processed juices. This activation can lead to microbial spoilage during storage, causing significant economic losses (Menezes et al., 2019).

To obviate the quality problems caused by thermal processing, several non-thermal technologies have been introduced for safeguarding the quality of fruit juices mostly during processing and subsequent storage. Some of these novel technologies include ultraviolet irradiation (UV), pulsed electric field (PEF), high-pressure processing, high-power ultrasonication, ozonation and cold plasma which are effective at temperature below 50 °C and thus much lower reaction rates are generated by these technologies (Silva et al., 2020; Tiwari et al., 2009; Umair et al., 2022).

Non-thermal processing of fruit juices retains nutritional ingredients without compromising their physicochemical and sensorial properties, which has been reported for a wide range of juices such as Tiger nuts, watermelon juice, and other fruit juices (Bevilacqua et al., 2018; Bhattacharjee et al., 2019; Roobab et al., 2018). Besides, non-thermal technologies promote sustainable food production by efficient energy use, no or low waste produced, and maximizing the use of resources which could promote the adoption of a circular economy and the achievement of the Sustainable Development Goals set forth by the United Nations (Arshad et al., 2022).

In order to extend the shelf life of fruit juices, ultraviolet (UV) irradiation has been used as a promising non-thermal technique for enzyme inactivation and microbial inhibition. UV irradiation inactivates spoilage and pathogenic microorganisms by exposing the target product to UV radiation while exerting minimal changes on its chemical, nutritional properties, and sensorial quality of the fruit juice (Assatarakul et al., 2012). UV irradiation has been investigated in combination with other non-thermal technologies known as hurdle concept which entails the use of a deliberate and intelligent combination to achieve synergistic effect in the preservation of post-processing quality and shelf-life extension (Alabdali et al., 2020; Carrillo et al., 2018). Hurdle technology is a food preservation technique that involves the use of multiple techniques or hurdles to prevent the growth of microorganisms and extend the shelf life of food products (Alabdali et al., 2020).

UV radiation treatment of fruit juices has been monitored to inhibit various quality degrading enzymes, e.g., peroxidase (POD), polyphenol oxidase (PPO), pectin methyl esterase (PME), and lipoxygenase (LOX) (Aneja et al., 2014). We aimed in this review to evaluate recent information on the efficacy and application of the UV irradiation combined with other non-thermal technologies (e.g., UV + PEF, UV + mild heat) on the physicochemical quality characteristics, microbial inhibition and enzyme inactivation of fruit juices to identify research gaps and future opportunities for the development of functional foods.

Thermal-, Non-thermal Processing and Hurdle Concept in Fruit Juices

Chemical, microbiological, and enzymatic interactions are the main causes of fruit juice deterioration (Bhattacharjee et al., 2019). They cause the juice to darken and discolor as a result of their reaction with dissolved oxygen. On the other hand, non-enzymatic browning via the Millard reaction is also responsible for the browning of fruit juices during processing. Fruit juices have traditionally been preserved by thermal processing to retard microbial growth and inactivate enzymes in juices. The minimally processed fruit sector is one of the industry's fastest expanding sectors, as consumers desire goods with a higher degree of freshness and safety for consumption. A number of milder fruit preservation techniques, some of which are currently in use commercially, had been investigated, i.e., "non-thermal food processing technologies" to balance these tendencies without compromising on food product safety. On the other hand, thermal pasteurization involves the heat transference in juice processing via conduction and convection mode of transmission. The goal of thermal pasteurization is to kill pathogens and significantly reduce the amount of spoilage microorganisms. Low temperature-long time (LTLT) and high temperature-short time (HTST) methods are two types of traditional thermal pasteurization employed in the juice processing. LTLT pasteurization includes heating a food to a temperature around 63 °C for at least 30 min, while HTST pasteurization is used in fruit juices with holding periods of 15 s at 72 °C. Despite the fact, thermal treatments have some effectiveness in maintaining microbial quality, but these affect color, flavor, and nutritional properties followed by protein denaturation, loss of vitamins, and volatile sensory components in fruit juices (Menezes et al., 2019) which reported that mold ascospores that cause food deterioration and loss of revenue can be reactivated by heat processing.

To overcome the quality losses in heat-processed juices, non-thermal processing is an effective means to retain the physiochemical, nutritional, and sensory properties with extended shelf life. Non-thermal technologies have drawn a lot of interest in recent years as additive-free, cost-effective, and eco-friendly food processing technologies to replace thermal methods of food processing. According to Bevilacqua et al. (2018), some non-thermal techniques used in juice processing include high-pressure processing (HPP), ultrasonication (US), ozonation (O_3), membrane filtration (MF), and high-pressure CO_2.

Ultraviolet irradiation has several technological benefits over other non-thermal concepts due to its low maintenance and installation costs, minimum energy consumption, and ability to preserve food without causing any adverse side effects. However, the UV source efficiency, which includes the quantity and kind of UV light sources, flow rate and pattern, effectiveness of UV reactor mixing, and properties of the food to be treated (e.g., composition of the product, and viscosity), is related to the energy efficiency of the UV system (Müller et al., 2014). It was found that compared to heat pasteurization and other non-thermal technologies (e.g., HPP, MF, and PEF), the total energy consumption of a UV system is much lower (Delorme et al., 2020). Moreover, Delorme et al. (2020) emphasized that the limited application of UV when used alone could be addressed by combining UV irradiation with other interventions such as non-thermal processing for additive and/or synergistic effects. UV light wavelength in the range of 100 to 400 nm in the electromagnetic spectrum has been classified into several groups such as UV-A, UV-B, UV-C, and UV-V (Rifna et al., 2019). The UV system described in our earlier work was made up of a stainless-steel cylinder with a 5.74-cm diameter and a 22.0-cm length. A glass tube with a diameter of 2 cm and a length of 24.50 cm was put within the stainless-steel cylinder, encircling a 6-Watt UV lamp (Visuthiwan & Assatarakul, 2021). The juice sample is circulated through a thin layer between the glass tube and the outer cylinder to be exposed to the UV radiation. The low-pressure mercury lamps emit UV-C radiation on the exposed juice sample. Fruit juice variety, absorptivity, suspended particles in the liquid, and soluble solids, all affect how much UV-C radiation penetrates the liquid. The intensity of the UV-C light's penetration into the liquid decreases as the amount of soluble solid increases (Ramesh et al., 2018). Microorganisms (e.g., bacteria, viruses, and protozoa) are susceptible to the germicidal effects of UV-C (Shah et al., 2019). UV-C irradiation at 400 J/m^2 irradiation dose was recommended for fruit juice pasteurization and microbial inactivation (Bhattacharjee et al., 2019). The effectiveness of UV will also be influenced by a number of other instrumental factors, including the type and length of the lamp being used, turbidity, viscosity, and the density and absorbance coefficient of the food material being treated.

In the preservation of fruit juice, hurdle technology involves the use of several techniques to prevent the growth of microorganisms and maintain the quality of the juice. Some hurdles that can be used in the preservation of fruit juice with the combination of UV include the use of high-pressure processing (HPP) and pulsed electric field (PEF), which can kill microorganisms. As an example, UV irradiation has been employed with HPP technology to preserve nutritional ingredients, color, and flavor qualities of fresh juice products (Koutchma et al., 2016). However, the success of UV technology in hurdle systems depends on various factors, including the intensity, exposure time, and wavelength of the UV light, as well as the characteristics of the juice. The combination of UV treatment with other hurdles, such as pasteurization, refrigeration, or chemical preservatives has shown to enhance its effectiveness and provide a comprehensive approach to food preservation. By combining these different hurdles, hurdle technology can provide a more effective and comprehensive approach to preserve fruit juice, ensuring that it remains safe and high quality for a longer period of time. In a recent study, Bigi et al. (2022) concluded that the hurdle concept overcomes the limitations related to the single technologies, broadens their efficiency and application range, and minimizes their impact on food quality. However, further studies were recommended to better understand the mechanisms of mutual interaction among these techniques when combined together in specific conditions, in view of their scaling-up for commercial applications.

This study summarizes the published studies on the use of UV radiation in combination with other non-thermal processing (hurdle concept) for the preservation of fresh juice quality in recent years. Furthermore, these effects on microbial, physical, chemical, sensory, and shelf-life attributes in fruit juices have been provided in details.

An Overview of Published "Review Papers" on Hurdle Technology Using UV Irradiation in Fruit Juices

Combining non-thermal treatments, which are used in the food industry, has demonstrated the ability to improve processing efficiency at lower treatment intensities while also overcoming the limitations of single technologies (Zhang et al., 2019). A review paper on the effects of UV light and HPP processing on the nutritional value and quality of fresh fruit and vegetable juices showed that, under the conditions needed to achieve a 5-log reduction of pathogenic microorganisms, only a minor number of physicochemical properties, vitamin content, and antioxidant activity were degraded (Koutchma et al., 2016).

Delorme et al. (2020) mentioned that UV-C radiation as environment-friendly non-thermal technology can be considered an effective method for inactivating pathogenic and spoilage microorganisms in dairy products; however, the process parameters such as exposure time, UV dose, wavelength, UV light source, product type, chemical composition, viscosity, turbidity, opacity, and roughness, equipment conformation and geometry, and microorganism properties all affect how effective the procedure is. According to Shah et al. (2019), when combining ultraviolet with other procedures at low intensities, the dosage and exposure of UV-C to the fruit juice should be appropriately controlled. According to Bevilacqua et al. (2018), the advantages of hurdle technologies such as UV + mild heat, high hydrostatic pressure, and other non-thermal treatments depended on the food matrix, the compatibility of the components used in each method, and the ease with which the food industry can implement each method. They also recommended more research on non-thermal electrical treatments, such as radiation processing, high-pressure processing, ultrasound, inert gas treatments, cold plasma processing, and membrane processing, in order to manage processing systems and optimize resources, maintain nutritional value and organoleptic properties, and provide processing conditions for the industrial scale validation of these technologies. In order to examine the inactivation of microorganisms and/or the preservation of pomegranate juice quality features, particularly during the shelf life, Putnik et al. (2019) focused on combining two or more non-thermal treatments (hurdle concept).

The hurdle technology strategy of preserving the natural value of foods over long periods of time was proven in a more recent study by Putnik et al. (2019); it was also concluded that UV radiation was a useful addition to hurdle technologies. According to Roobab et al. (2018), utilizing mild heat in addition to UV irradiation is extremely promising for combating more resistant bacteria species and spores. According to Bhattacharjee et al. (2019), non-thermal processing of watermelon juice has been successfully studied in order to minimize microbial deterioration and retain nutritious components through less enzyme and microbial activity. Hurdle technology using ultraviolet (UV) technology in fruit juice processing can have several positive effects on the circular economy and contribute to achieving Sustainable Development Goals (SDGs). According to Arshad et al. (2022), incorporating UV technology into hurdle technology for fruit juices aligns with several SDGs, including those related to responsible consumption, environmental sustainability, health, and economic growth. It promotes a more circular and sustainable approach to food processing, reducing waste and resource consumption while enhancing safety and product quality.

Based on the published review papers mostly from the last decade ago (Table 1), using hurdle technology, which is capable of increasing organoleptic and sensory features and ensuring the microbiological safety of foods, could help counteract the negative impact of conventional thermal technologies. However, in a review paper, Aaliya et al. (2021) identified important challenges and future directions for hurdle technologies research. These included the following: (1) gaining a comprehensive understanding of the physicological conditions under which microbes respond to various stress adaptation processes in order to prevent cross-tolerance reactions and (2) estimating and assessing the synergistic effects of hurdle approach in order to prevent antagonistic effects. (3) In a laboratory setting, challenge testing and process validation for predictive microbiology are required. (4) Future uses should carefully plan low-cost hurdle technologies that have minimal quality deterioration and high inactivation efficacy. (5) Food researchers should follow the global harmonization of hurdle technologies in order to harmonize the processing conditions stated in different research findings.

Effect of Hurdle Technologies Using UV Irradiation on Microbial Quality of Fruit Juices

Hurdle technology using UV technology has a profound and positive impact on the microbial quality of fruit juices. It provides a safe and effective means to reduce and eliminate harmful microorganisms, extending shelf life and enhancing food safety while preserving the sensory qualities of the juice. This technology contributes to higher microbial quality, ensuring that consumers can enjoy safe and microbiologically stable fruit juices. The various studies obtained from the literature on the application and impact of UV irradiation in association with other non-thermal technologies on the microbial quality of fruit juices are presented in Table 2 and Fig. 1 and discussed in this section. In an early study, UV irradiation and PEF were used in conjunction to achieve adequate total microbial inactivation (7.1 log decrease) and to improve product quality (e.g., reducing PPO and POD activity) in comparison to heat pasteurization (Yin et al., 2015). Furthermore, the order in which the technologies were used such as UV + PEF or PEF + UV did not have an impact on the level of microbial inactivation as a whole. The future utilization of these combined technologies for fruit juice processing especially freshly squeezed apple juice was proposed in that early study. In apple juice, the synergistic effects of UV-A irradiation and fumaric acid addition (0.1%) reduced the contamination by *E. coli* O157:H7, *S.* Typhimurium and *L. monocytogenes* up to 3.43 log (Jeon & Ha, 2020). In the other hurdle concept, UV-C (14 mJ/cm^2) and ascorbic acid (300 mg/kg) addition showed 5-log reduction of *E. coli* in apple juice (Usaga et al., 2017). Up to 7 log-reduction of *S. cerevisiae* was achieved following

Table 1 An overview of published "review papers" on hurdle technology using UV irradiation in fruit juices

Year	Title	Processing method	Food product	Key finding (s) and perspectives	Reference
2015	Effects of ultraviolet light and high-pressure processing on quality and health-related constituents of fresh juice products	• Ultraviolet (UV) light and high-pressure processing (HPP)	• Fruit and vegetable juices	• UV light and HPP are approved by regulatory agencies and recognized as one of the simplest and environmentally friendly ways to destroy pathogenic organisms • More studies on the effects of UV light and HPP on both fruit and vegetable enzymes such as PPO, POD, PME, and LOX	Koutchma et al. (2016)
2017	Hurdle technology: A novel approach for enhanced food quality and safety: A review	• Hurdle technologies	• Food products	• Huge investment cost and the lack of proper regulations are the main drawbacks of the hurdle concept • Hurdle strategies are capable of improving organoleptic and sensory characteristics and ensuring the microbial safety of foods	Khan et al. (2017)
2018	Non-thermal technologies for fruit and vegetable juices and beverages: overview and advances	• High-pressure processing, ultrasound, radiation processing, inert gas treatments, cold plasma, and membrane processing	• Fruit and vegetable juices	• Optimization of combined technologies approaches is useful to validate these technologies at the industrial scale	Bevilacqua et al. (2018)
2018	Comparison the effects of thermal and non-thermal technologies on pomegranate juice quality	• Ultraviolet light, high hydrostatic pressure, pulsed electric field, ultrasound, and cold plasma	• Pomegranate juice	• Operating conditions of each approach have to be optimized and adjusted for each product (e.g., clear or cloudy juice) • Hurdle technology could be regarded as more affordable for processing pomegranate juice at the industrial scale	Putnik et al. (2019)
2018	The impact of non-thermal technologies on the microbiological quality of juices	• Non-thermal process (ultrasonication, pulsed electric field, high-pressure processing, irradiation, and their combinations)	• Fruit and vegetable juices	• Non-thermal process can meet consumer demand for clean-label, safe, and wholesome products without compromising their nutritional properties • Further studies are needed to make these technologies more affordable and to scale them up in order to satisfy the needs of the juice industry	Roobab et al. (2018)

Table 1 (continued)

Year	Title	Processing method	Food product	Key finding (s) and perspectives	Reference
2018	Non-thermal technologies and its current and future application in the food industry	• Non-thermal technologies	• Food products	• The combination treatment may be a more effective processing technique for the food industry • Producing industrial-scale equipment, defining clear mechanisms, developing standards, and correcting the misconceptions of consumers about non-thermal processing are important	Zhang et al. (2019)
2019	Novel thermal and non-thermal processing of watermelon juice	• Pulsed electric field (PEF), ultraviolet irradiation (UV), sonication, ohmic heating (OH), high-pressure processing (HHP), high-pressure carbon dioxide (HPCD), nanofluid thermal processing (NFT), and membrane technology	• Watermelon juice	• Non-thermal processes showed positive results in reducing the microbial spoilage of watermelon juice and retaining the nutritional compounds • More studies are needed in terms of cost optimization and scalability of these processes to fulfill the needs of both the industry and consumer	Bhattacharjee et al. (2019)
2020	Innovative hurdle technologies for the preservation of functional fruit juices	• Hurdle technology non-thermal process + antimicrobial additives, thermal treatment, and ultraviolet or pulsed light)	• Fruit juice	• Hurdle technology could be a promising approach for the preservation of fruit juices • Hurdle technology has high efficiency and low impact on juice quality and characteristics • Hurdle technology requires optimization (i.e., still a gap in the research in combining two of the most promising hurdle technology techniques)	Putnik et al. (2020)
2021	Recent trends in bacterial decontamination of food products by hurdle technology: A synergistic approach using thermal and non-thermal processing techniques	• Hurdle technology	• Food products	• Combining thermal and non-thermal food processing methods has a synergistic effect against food spoilage microorganisms • Optimization and globalization of these hurdle combinations are an emerging field in the food processing sector	Aaliya et al. (2021)

Table 1 (continued)

Year	Title	Processing method	Food product	Key finding (s) and perspectives	Reference
2021	Ultraviolet Light Microbial Inactivation in Liquid Foods	• UV-C	• Food products	• UV-C effectiveness depends on the inherent medium properties (intrinsic characteristics) and the process parameters/environmental aspects (extrinsic characteristics) • Combining UV with other technologies has been demonstrating that this hurdle technology approach may be a promising potential strategy to improve microbial reduction or reduce the severity of the individual treatments	Souza and Koutchma (2021)
2022	Non-thermal food processing: A step towards a circular economy to meet the sustainable development goals	• Non-thermal processing	• Food products	• Non-thermal processing helps in implementing a circular economy to meet the United Nations-approved Sustainable Development Goals (SDGs) • The food industry should focus on the sustainability of zero-waste processing, waste management, and food packaging	Arshad et al. (2022)

Table 2 Impact of hurdle technologies using UV irradiation on microbial qualities of fruit juices

Fruit juice samples	Processing method	Treatment conditions	Conclusive findings	References
Açai (*Euterpe oleracea*) juice	UV-pulsed light (UV-PL) and low-pressure plasma (LPP)	UV-PL at 2 V (0.0857 J/cm^2), 6 V (0.6000 J/cm^2), 10 V(0.9473 J/cm^2), Xe LPP at 700 Torr	• *Salmonella* and coliforms were absent in processed samples. The initial microbial reduction was attributed to sub-lethal injuries instead of complete inactivation during storage	Linhares et al. (2020)
Apple cider	UV + microfiltration	UV 1.75 mJ/cm^2, pore size 0.8 µm	• The combined microfiltration and UV achieved 5-log reduction of *E. coli*, *C. parvum*, and *A. acidoterrestris*	Zhao et al. (2015)
Apple juice	UV-A and fumaric acid addition	0.03 mW/cm^2; 0, 10, 20, and 30 min, fumaric acid 0.05 or 0.1%	• Synergistic effect (UV-A and 0.1% fumaric acid) after 30 min was observed in *E. coli* O157:H7, *S.* Typhimurium and *L. monocytogenes* and were reduced up to 3.15, 2.21, and 3.43 log units, respectively	Jeon and Ha (2020)
Apple juice	UV-C + additives	14 mJ/cm^2	• UV-C at 14 mJ/cm^2 and 300 mg/kg ascorbic acid addition showed 5-log reduction of *E. coli*	Usaga et al. (2017)
Apple juice	UVC and ultra-high-pressure homogenization (UHPH)	UHPH 171 at 100 or 200 MPa, UV-C 7.2, 14.3, and 21.5 J/mL	• Both microorganisms' ascospores were inactivated by UV-C (1.8 J/mL). *T. macrosporus* were more resistant to UV-C than *N. spinosa*. A UV-C single pass at 21.5 J/mL enumerated 2.15 Log_{10} and 5.4 Log_{10} compared to UPPH	Sauceda-Gálvez et al. (2020)
Apple juice	UV-C and ultrasound (US)	UV-C at 254 nm (8 min) + US (35 kHz, 120–480 Watt, 30 min)	• US did not have much impact on *A. acidoterrestris* inactivation. UV-C decreased the spores drastically after 8 min than the thermal treatment	Tremarin et al. (2017)
Carrot-orange juice	UV-C, mild heat(H), and combination UV-C/H	UV-C light (UV-C, 1720 mJ/cm^2)	• UV-C/H therapy reduced *C. Parapsilosis* by 5.5 log cycles, whereas single UV-C and H treatments reduced it by 2.9 and 3.9 log cycles, respectively	Carrillo et al. (2020)
Carrot-orange	UV-C and mild heat	0–10.6 kJ/m^2, heated at 50 °C	• 4- to 7-log reductions of *S. cerevisiae* were achieved in the combined treatment (UV-C + heat) of juice samples	Carrillo et al. (2018)

Table 2 (continued)

Fruit juice samples	Processing method	Treatment conditions	Conclusive findings	References
Carrot juice	UV-C and thermal treatment	227.5 mJ/cm^2, 1.152 kJ/L, 5 cycles	• Mesophilic, psychotropic, lactic acid bacteria, and *Enterobacteriaceae* were retarded by UV-C and thermal process during days 0–12 than the fresh sample. Yeast and mold were absent in UV-C and thermally treated sample	Riganakos et al. (2017)
Clear and turbid fruit juices	UV-C assisted by mild heat	UV 390 mJ/cm^2, heat 50 °C	• UV-C inactivated *L. plantarum*, *E. coli*, and *S. cerevisiae* up to 2.4, 3.8, 1.6 log cycles for orange-tangerine juice and 3.6, 3.7, and 1.3 log cycles in orange-banana-mango-kiwi-strawberry juice, respectively	Fenoglio et al. (2020)
Carrot juice	UV-C and mild heat	UV 3.92 J/mL, 3.6 min at 60 °C	• Combined UV and heat treatment reduced over 5 log cycles of the most resistant pathogens (i.e., *E coli* O157:H7, *L. monocytogenes*, *L. plantarum*)	Gouma et al. (2020)
Food product	UV + ethanol	UV (6–504 mWs/cm^2) + ethanol (10–50%)	• More bacterial reduction as a result of the combination ethanol-UV treatments than by each treatment used alone	Ha and Ha (2010)
Grape juice	UV-C + addition of SO_2	683 J/L (1 min), 1366 J/L (2 min), 68,349 J/L (10 min), 13,670 J/L (20 min)	• UV-C reduced the microbes up to 3 log (0.68 kJ/L), 3.5 log (6.83 kJ/L), and 4.5 log (13.67 kJ/L), and SO_2 incremented more reduction along with UV treatment in the juice sample	Czako et al. (2018)
Grapefruit juice	UVC + trans- trans-cinnamaldehyde (CAH)	UV-C (0, 10, and 20 min), (trans-CAH) (0, 25, and 50 g/mL)	• 100 CFU/mL for 15 days was attained in treated juice treated with UV-C light and addition of trans-CAH	(Ochoa-Velasco et al., 2018)
Lychee juice	UV-C	0–74.88 J/cm^2	• First-order kinetic model determined microbial degradation was recommended and antioxidant properties were retained in treated juice	Visuthiwan and Assatarakul (2021)
Orange and apple juices	UV-C and ultrasound	Dyna-shock wave + UV-C	• UV-C + US inactivated *E. coli* O157:H7 in apple juice	Gabriel (2015)
Orange juice	UV-C (1.14 mW/cm^2) + mild heating (53 °C)	(1.14 mW/cm^2) + (53 °C)	• The hurdle treatment showed a microbial reduction (*E. coli* O157:H7) of 6.35 log CFU/mL	Pagal and Gabriel (2020)

Table 2 (continued)

Fruit juice samples	Processing method	Treatment conditions	Conclusive findings	References
Orange juice	UV-C and mild heat	19.75 J/L for 5 min, heat: 40 °C for 5 min	• UV-C could reduce mesophiles and molds + yeast up to 0.19 log, and their combination reduced 0.4 log. No microbial increments were noticed after 9 days of storage at 5 °C	Hernández-Carranza et al. (2021)
Orange-tangerine (OT) and orange-banana-mango-kiwi-strawberry (OBMKS) juice	UV-C, UVC-H, mild heat and antimicrobials	UV-C (0–390 mJ/cm^2, 50 °C, UV-C/H), and antimicrobials (1000 ppm vanillin plus 100 ppm citral)	• UV-C treatment with the addition of selected binary vanillin and citral mixes can result in *E. coli*, *L. plantarum*, and *S. cerevisiae* reductions of more than 5 logs in OT and OBKMS juice blends	Fenoglio et al. (2020)
Red prickly pear juice	UV-C and pH	UV-C (0–31.87 mJ/cm^2), time (15, 30, 60 min), pH (3.6, 7.0)	• Both pH 3.7 and 7 alongside the various irradiations affected microorganism inactivation effectively	Mesta-Vicuña et al. (2022)
Pineapple juice	UV reactor equipped by a quartz glass sleeve	3.1 mW/cm^2, 34.9 s	• *S. Typhimurium* was significantly lower after 9 weeks of storage	Mansor et al. (2017)
Pomegranate juice	UV + ultrasonication (US)	5.1 mW/cm^2 UV dose, 10 min US (200 Watt)	• UV + US has the potential to inhibit microbial activity at lower temperatures and periods than the standard pasteurization method. For microbiological outcomes, US pasteurization was more successful than UV pasteurization when applied alone	Alabdali et al. (2020)
Pomegranate juice	UV-C coupled microwave (MW) system	UV-C (254 nm) + MW (876 Watt)	• After three runs, the UVC–MW system with a t400 ml/min was the most successful treatment for yeast and bacteria inactivation, with roughly 6 cycle log decreases	Gómez Sánchez et al. (2020)
Tangerine and grapefruit juices	Ultrasonic atomization (USA) and UV-C	UV-C (0, 3.13, 1.64 J/mL), USA (6.06 J/mL)	• USA and UV-C in combination effectively inactivated spoilage *S. cerevisiae* in tangerine and grapefruit juices	Antonio-Gutierrez et al. (2017)
Verjuice	UV-C and mild heat treatment, and combination	0.57 J/cm^2, 0.37 J/cm^2 and 48.3 °C, 0.25 J/cm^2 and 51.3 °C	• Complete inactivation of *S. cerevisiae* (~5 log) was attained in UV-C (0.25 J/cm^2) and mild heat (51.3 °C) treated juice	Kaya and Unluturk (2019)

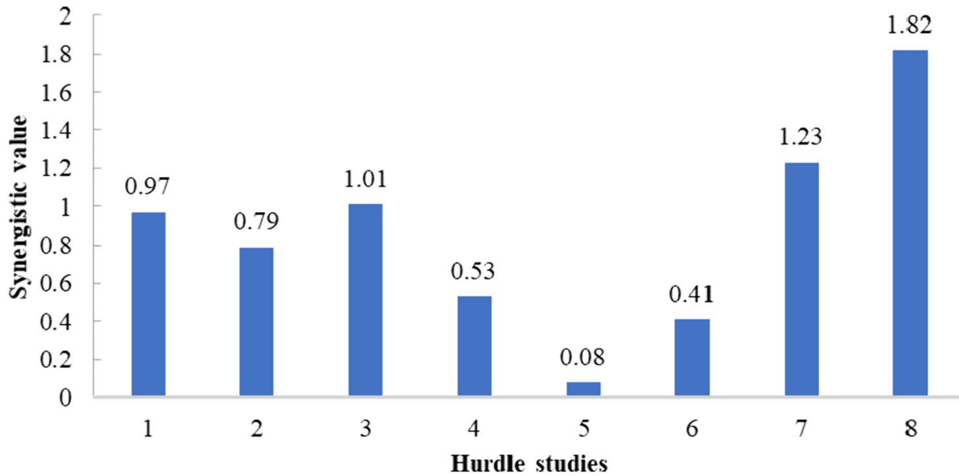

Fig. 1 Synergistic value of hurdle concept using UV irradiation for microbial decontamination in fruit juices. Note: Synergistic effect is calculated as the combined effects of non-thermal processing divided by the summed single effect of each non-thermal processing (Ha & Ha, 2010). A positive synergistic value indicates the benefit of combining multiple non-thermal processing, while a negative result shows the decreased benefit effects and a zero value means only an additive effect not a synergistic one. The numbers indicate as follows: (1) UV + ethanol treatments reduced *S. aureus*, *S. enterica* Typhimurium and *E. coli* (Ha & Ha, 2010); (2) UV-C (0–10.6 kJ/m^2) and mild heat (50 °C) reduced *S. cerevisiae* in carrot-orange juice (Carrillo et al., 2018); (3) UV-C + mild heat (50 °C) reduced mesophiles, mold, and yeast in orange juices (Hernández-Carranza et al., 2021); (4) UV-C and mild heat (50 °C) reduced *S. cerevisiae* in verjuice (Kaya & Unluturk, 2019); (5) UV + ultrasonication reduced yeast and mold count in pomegranate Juice (Alabdali et al., 2020); (6) UV-C + mild heat + 100 ppm citral + 1000 ppm vanillin reduced *E. coli*, *L. plantarum*, and *S. cerevisiae* in orange-tangerine (Fenoglio et al., 2022) and orange-banana-mango-kiwi-strawberry during 7 days of cold storage (Ferreira et al., 2020); (7) UV-C + coupled microwave reduced *Saccharomyces cerevisiae* and *Escherichia coli* in pomegranate juice (Gómez Sánchez et al., 2020); (8) UV-A + fumaric acid (0.1%) reduced *E. coli* O157:H7, *S.* Typhimurium and *L. monocytogenes* in apple juice (Jeon & Ha, 2020)

UV-C + mild heat (50 °C) treatment of carrot juice samples (Carrillio et al., 2018). The other study also showed that combined UV and mild heat (50 °C) treatment reduced more than 5 log cycles of the most resistant pathogens (i.e., *E coli* O157:H7, *L. monocytogenes*) in carrot juice. The application of UV-C (1.14 mW/cm^2) + mild heating (53 °C) showed a microbial reduction (*E. coli* O157:H7) of 6.35 log CFU/mL in orange juice. During cold storage for 9 days, no microbial increments were observed after UV-C and mild heat treatment (Hernández-Carranza et al., 2021). Patulin, a mycotoxin from molds, particularly *Aspergillus* spp., *Penicillium* spp. and *Byssochlamys* spp. contamination in apple juice concentrate decreased up to 5% after UV exposure at 99.4 mJ/cm^2, with the proportion of patulin followed by first-order kinetic modeling with an exponential relationship between UV exposure and the microbial inhibition (Yin et al., 2015). In comparison to UV radiation at 254 nm and Far UV lights at 282 nm, the inactivation of *E. coli* O157:H7 after exposure to Far UV light at 222 nm was greater in apple juice (Usaga et al., 2014). UV-C (38 W/m^2) in apple juice at different soluble solid concentrations (12, 25, 30, 40, 50, 60, and 70°Brix) affected the inactivation of *N. fischeri* ascospores mold by approximately 4-log reduction (Pinto et al., 2022).

It should be noted that the yearly UV validation of monitoring the efficacy of frequency for commercial UV (CiderSure 3500) juice processing units is recommended to ensure safety against food-borne pathogens and spoilage microorganisms (do Prado et al., 2019). The use of UV-C reduced the spore counts and biofilm formation of *Alicyclobacillus* spp. in industrialized orange juice, being a promising alternative for the control of *Alicyclobacillus* spp. especially for the *A. acidocaldarius* spp. (Ferreira et al., 2020). Additionally, UV-C combined with nisin potentially eliminated *A. acidoterrestris* spores in industrialized orange juice and maintained the final quality without any degradation of vitamins or other nutritional components (Pala & Toklucu, 2013).

The microbial loads of grapes were completely inactivated after UV-C treatment at a dose of 25.2 J/mL (Groenewald et al., 2013). UV-C employed at a dosage level of 116.7 J/mL in freshly squeezed grape juice showed 3.759, 4.133, and 1.604 log CFU/mL reduction to *E. coli* K-12, lactic acid bacteria, and food-borne yeasts, respectively (Czako et al., 2018). UV processing inactivated *Alicyclobacillus* spp. spores in processed grape juice and contaminated wash water used in fruit processing which was also decontaminated (Mansor et al., 2017). The combination of UV-C (13.67 kJ/L) and SO_2 reduced the microbial contamination up to 4.5 log in the grape juice samples (Czako et al., 2018). An inactivation of up to 9.10 log in *S.* Typhimurium was reported after UV exposure at doses of 15.45–27.63 mJ/cm^2 in pummelo juice (Shah et al., 2019). UV-C irradiation with additional Dean Vortex technology was effective in pineapple juice as evidenced by 5 log CFU/mL of *S.* Typhimurium at a dosage level of 13.8 mJ/cm^2, which was in line with the FDA standards (Kim et al., 2021). UV-C treatment (0.0–2.36 J/cm^2) at 254 nm in grapefruit juice inactivated *E. coli* ATCC 25922 and one strain of *S. cerevisiae* with no significant changes on citric, malic, tartaric acids, naringin, hesperidin and neohesperidin, total phenolics, ABTS+, pH, °Brix, titratable acidity, and color of the grapefruit juices (La Cava & Sgroppo, 2019). Additionally, to forecast the shelf life of UV and thermally modified fruit juices, kinetic modeling has been examined for color and bioactive compounds, although the majority of kinetic models explored in the microbiological safety of fruit juices are traditional, such as zero-order, first-order, and second-order kinetics. However, alternative models have been used to track the kinetics of vitamin C and anthocyanin degradation in thermally processed guava pulp, cupuacu (*Theobroma grandiorum*) nectar, and blackcurrant juice. The effects of UV light on inoculated *A. acidoterrestris* spores in apple juice demonstrated that *A. acidoterrestris* inactivation follows a first-order kinetic (Ochoa-Velasco et al., 2018).

The combined effects of UV + ethanol treatments resulted in greater reductions in *Bacillus cereus* F4810/72, *Cronobacter sakazakii* KCTC 2949, *Staphylococcus aureus* ATCC 35556, *Escherichia coli* ATCC 10536, and *Salmonella enterica* Typhimuriumthan when either treatment was applied (La Cava & Sgroppo, 2019). Moreover, the synergistic values of the combined effects of UV + ethanol were reported up to 2.32. An increase in benefit from combining different therapies is shown by a positive synergistic effect value, whereas a loss in benefit is indicated by a negative result. Zero indicates that there is no synergistic, but rather additive, effect of combining the separate treatments. Figure 1 shows that hurdle technologies using UV irradiation have synergistic effects to inhibit the microbial load of fruit products. Fenoglio et al. (2020) also demonstrated that UV-C treatment with the addition of selected antimicrobials (vanillin plus citral) could result in *E. coli*, *L. plantarum*, and *S. cerevisiae* reduction for more than 5 logs in orange-tangerine and orange-banana-mango-kiwi-strawberry juice blends. Kaya and Unluturk (2019) reported a complete inactivation of *S. cerevisiae* (~5 log) in verjuice after treatment with the combination of UV-C (0.25 J/cm^2) and mild heat (51.3 °C). Ultrasonic atomization and UV-C in combination effectively inactivated spoilage with *S. cerevisiae* in tangerine and grapefruit juices (Antonio-Gutierrez et al., 2017).

Overall, the management of microbiological and biochemical quality control on heat- and UV-treated fruit juices is supported by the application of food kinetics, which is a potent tool to uncover fundamental reaction mechanisms. However, compared with traditional thermal pasteurization, non-thermal hurdles like UV and other techniques may offer a higher chance for improved microbiological safety and shelf life in fruit juices.

Effect of Hurdle Technologies Using UV Irradiation on Physicochemical Quality and Enzymatic Activity of Fruit Juices

The various effects of hurdle technologies on physicochemical quality characteristics are provided in Table 3. In a recent study, grape juice extracted from post-harvest stored organic grapes and treated with UV-C at a dose of 65.6 J/m^2 revealed increased levels of phenolic compounds with no interference with the basic physicochemical composition including color values and hue angle, pH, total titratable acidity, and total soluble solids (Pinto et al., 2022). Consistently, UV-C treatment at the FDA-suggested dose of 40 mJ/cm^2 retained polyphenolic compounds in apple juice with significant changes in vitamin contents. It was proposed that more research be done on low oxygen exposure to enable better vitamin levels. Bioactive components were found to be higher in apple juice samples with combined UV-C and moderate heat treatment compared to pasteurization (Yıkmış et al., 2021). The other study also showed that UV-C + mild heat improved the functionality of carrot juice (Carrillo et al., 2020). In pomegranate Juice, UV + ultrasound treatment during the pasteurization process preserved the bioactive compounds (Alabdali et al., 2020). La Cava and Sgroppo (2019) reported no negative impact on the physicochemical properties of grapefruit juice after treatment with UV-C + mild heat. However, Czako et al. (2018) reported that UV-C + addition of SO_2 increased turbidity in grape juice. UV-C + ultrasonic atomization revealed minimal changes in terms of color, pH, and TSS in tangerine and grapefruit juices (Antonio-Gutiérrez et al., 2017).

Visuthiwan and Assatarakul (2021) demonstrated that even using UV-C alone had no effect on pH, Brix, titratable acidity, total flavonoid concentration, or antioxidant activity in lychee juice. The treatment of apple juice by UV alone showed no major changes in color and better retention of phenolics and color (Yang et al., 2019). UV-C-treated pitaya juice preserved phenolic compounds and retarded mesophilic bacteria and yeasts including *Zygosaccharomyces bailii* after 10 days of storage at 4 °C (Pendyala et al., 2020). Phenolics and ascorbic acid contents of lemon, orange, papaya, and grape juices were decreased in UV-treated compared to untreated fresh juice samples (Ramesh et al., 2018). The effects of UV-C treatments (12.6 and 25.2 J/mL doses) on phenolics, antioxidant activity, and total anthocyanins of red and white grapes showed that all the tested parameters were well maintained after the UV-C exposure (Groenewald et al., 2013). Furthermore, in the pineapple-mango juice blend, UV-C at a dose of 8.4 mJ/cm^2 showed higher values of ascorbic acid, total

Table 3 Impact of hurdle technologies using UV irradiation on physicochemical quality and enzymatic activity of fruit juices

Fruit juice samples	Processing method	Treatment time and dose	Physiochemical and enzymatic changes reported	References
Açai (*Euterpe oleracea*) juice	High-power ultrasound (US), UV-pulsed-light, and low-pressure plasma (LPP)	UV 2 V (0.0857 $J.cm^2$), 6 V (0.6000 $J.cm^2$), and 10 V (0.9473 $J.cm^2$)	• PEF increased sugar content (glucose and fructose) except US + LPP amino acid betaine that improved the bioaccessibility of vitamin C by 8%	Linhares et al. (2020)
Apple juice (not-from-concentrate (NFC)	UV	UV-C 254 nm, 41 min	• UV showed no major changes in color, and UV tends to possess better retention of phenolics and color	Yang et al. (2019)
Apple juice	UV-C and moderate heat treatment	UV-C (84.6 and 169.1 mJ/cm^2) at 40, 45, 50, 55, and 60 °C	• Bioactive components were found to be higher in samples with all combined processes compared to pasteurization	Yıkmış et al. (2021)
Aloe vera gel and pitaya blend	UV-C + pH	16.5, 27.7, and 40 mJ/cm^2, 6.63, 11.05, 16.57 s, pH 3.5 and 5.5	• pH and UV-C treatment significantly affected L*, a*, and b*. But the UV-C dose did not have any effect on the physicochemical properties	Meléndez-Pizarro et al. (2020)
Apple juice	UV-A and fumaric acid addition	0.03 mW/cm^2, 0, 10, 20, and 30 min, fumaric acid addition (0.05 or 0.1%)	• UV samples showed no changes in non-enzymatic browning index, pH, and total phenolic content. But L* value slightly decreased, a* and b* showed the least changes	Jeon and Ha (2020)
Carrot juice	UV-C and mild heat	UV (3.92 J/mL, 3.6 min), heat: 60 °C	• UV-C radiation with mild heat improved PME and PPO inactivation. pH was constant in treated samples, but untreated control decreased in pH on the 7th day	Gouma et al. (2020)
Carrot juice	UV-C and thermal treatment	227.5 mJ/cm^2, 1.152 kJ/L, 5 cycles	• Lower a* and b* values and browning index were obtained in UV-C samples compared to thermal treatment. Viscosity, optical density, density, pH, and turbidity were similar in UV-C and heated samples	Riganakos et al. (2017)
Carrot-orange juice	UV-C, mild heat (H), and combination UV-C/H	UV-C light (UV-C, 1720 mJ/cm^2)	• UV-C/H retained juice color, pH, TSS, and turbidity, with greater total phenols (302.1 g/mL) than the control (TPC of 205.0 g/mL). PME was reduced by 42–45% for the H and UV-C/H treatments, respectively	Carrillo et al. (2020)

Table 3 (continued)

Fruit juice samples	Processing method	Treatment time and dose	Physiochemical and enzymatic changes reported	References
Clear and turbid juices (melon, orange-tangerine, orange, orange-carrot)	Shortwave UV-C light	Dosage of UV-C: 0–1720 mJ/cm^2, 0 and 15 min	• UV-C showed higher transmission, low absorption, and turbidity. However, particle aggregates slowed the disinfection process in the most turbid-tested juices	Fenoglio et al. (2020)
Grape musts and wine	UV-C	30 min, UV-C 5.5 kJ/L (2.3 J/cm^2)	• Volatile molecules such as terpenes and C13-nor-isoprenoids showed changes. Model tests revealed that linalool was rather stable, but UV-C exposure destroyed β-damascenone	Golombek et al. (2021)
Grapefruit juice	UV-C + mild heat	39.6 J/L and 65.0 °C	• Changes in the physicochemical properties were not observed	La Cava and Sgroppo (2019)
Grape juice	UV-C + addition of SO_2	683 J/L (1 min), 1366 J/L (2 min), 68,349 J/L (10 min), 13,670 J/L (20 min)	• UV-C-treated grape juice showed increased turbidity with or without addition of SO_2	Czako et al. (2018)
Lychee juice	UV-C	0–74.88 J/cm^2	• UV-C had no effect on pH, Brix, percent titratable acidity, total flavonoid concentration, or antioxidant activity	Visuthiwan and Assatarakul (2021)
Pineapple juice	UV reactor equipped by a quartz glass sleeve	3.1 mW/cm^2 and 2.5 mW/cm^2, 34.9 s and 19.86 s	• pH and TSS were lower changes. All juices showed a significant decrease in ascorbic acid. Darker color was observed compared to the untreated juice	Mansor et al. (2017)
Pomegranate juice	UV and ultrasonic (US) and combined UV + US	50 °C, 3.5 L/min flow rate and 5.1 mW/cm^2 UV dose, and 10 min US (200 Watt)	• UV + US during the pasteurization process preserved the bioactive chemicals that are already present	Alabdali et al. (2020)
Tangerine and grapefruit juices	Ultrasonic atomization (UA), UVC-light, and their combination	UV-C (0, 3.13, 1.64 J/mL), UA energy of 37,648 Joule/unit time, 9.42 min	• UA + UVC revealed minimal changes in juices in terms of color, pH, and TSS due to the short content of microdroplets with the UVC	Antonio-Gutiérrez et al. (2017)
Wheatgrass juice	UV-C, HHP, and thermal process	UV-C 254 nm	• UV-C light and HHP would be suitable alternative to thermal processing. UV-C treatment increased chlorophyll content while retaining antioxidants	Ali et al. (2020)

Table 3 (continued)

Fruit juice samples	Processing method	Treatment time and dose	Physiochemical and enzymatic changes reported	References
White grape juice	UV-A and UV-C	UV-A (350 nm; 14.8 mW/cm^2), UV-C (254 nm; 19.7 mW/cm^2)	• A 5-log drop in UV-C treatment resulted in a loss of health-benefitting compounds such as vitamin C, total phenolic content, and total antioxidant capacity	Ramesh et al. (2018)

phenolic compounds, and total antioxidant activity than those of heat treatment (90 °C for 5 min) during 9 weeks of cold storage (Kaya & Unluturk, 2019).

Using a laminar flow UV system, an efficient inactivation of endospores in watermelon juice was reported with no major changes in the concentration of ascorbic acid, volatile aroma, or flavor components (Aguilar et al., 2018). Ultraviolet and visible light (UV–Vis) had no negative effects on properties (e.g., color values, acidity, vitamin C content, sugar content); however, it was effectively inactivated enzyme in peach juices of different varieties (Sauceda-Gálvez et al., 2021). Pala and Toklucu (2013) reported that UV-C treatment (36.09 kJ/L) in orange juice resulted in no negative impact on chemical quality parameters such as organic acid content, antioxidant capacity, and phenolic compounds but little impact on the ascorbic acid content, aroma, and flavor characteristics of juice. Based on such findings, optimization of UV-C dose was suggested to guarantee microbial safety in the context of retaining the fresh-like characteristics of juice. A scale-up study on orange juice and sweet lime showed that the combined effect of non-thermal techniques consisted of UV and ultrasound to create fruit juices that are high in nutrients and have a long shelf life, opening the door to widespread commercialization of the technology (Khandpur & Gogate, 2015).

From the studies in terms of physicochemical properties, it could be derived that the hurdle technology which uses non-thermal technologies instead of pasteurization is frequently used in conjunction with various hurdles, such as heat treatment, UV or pulsed light, and antimicrobial compounds, to provide synergistic effects and enhance the overall quality of (functional) juices. Putnik et al. (2020) concluded in a review paper that because hurdle technology is effective and has no effects on the qualities of the juice, it may be a viable method for preserving fruit juices; however, optimization of all processing parameters is still necessary.

Effect of Hurdle Technologies Using UV Irradiation on Sensorial Quality and Shelf Life of Fruit Juices

The shelf life of fruit and fruit products should be extended by some interventions and treatments to prevent from spoilage. On the other hand, the creation of simple, low-cost, energy-efficient methods for storage without refrigeration that could be used to preserve fruits and fruit products was the main objective for the design of these combined approaches (hurdle concept). The combined use of UV-C (21.5 J/mL) and ultra-high-pressure homogenization (300 MPa) considerably altered the overall flavor and detectable aroma of cloudy apple juice, even if the treated samples' criteria for taste were equal to those of the raw

Table 4 Impact of hurdle technologies using UV irradiation on sensorial quality and shelf life of fruit juices

Fruit juice samples	Processing method	Treatment time and dose	Conclusive findings	References
Cloudy apple juice	UV-C + pressure homogenization (UHPH)	UV-C at 21.5 J/mL + UHPH at 300 MPa	• The treated samples were similar to the raw juice in the other parameters related to taste (sweetness, sourness, freshness, and texture)	Sauceda-Gálvez et al. (2021)
Apple juice	UV-C and moderate heat treatment	UV-C doses between 84.6 and 169.1 mJ/cm^2 at 40–60 °C	• UV-C is an adjunctive treatment to thermal pasteurization to minimize the heat intensity to give prolonged shelf life and eliminate the effect of heat pasteurization on the nutritional components of juice	Yıkmış et al. (2021)
Apple juice	UV	UV-C 254 nm, 41 min	• UV-treated samples stored at 4 ± 1 °C extended shelf life 3 weeks longer than freshly squeezed juice	Yang et al. (2019)
Apple juice	UVC and ultra-high-pressure homogenization	UHPH 171 at 100 or 200 MPa, UV-C (7.2, 14.3, and 21.5 J/mL)	• The nutritional and sensory characteristics were retained in the juice	Sauceda-Gálvez et al. (2020)
Carrot juice	UV-C and thermal treatment	227.5 mJ/cm^2, 1.152 kJ/L, 5 cycles	• UV-C-treated carrot juice had better sensory characteristics compared to the thermally processed, which could extend the shelf life of carrot juice by 8 days	Riganakos et al. (2017)
Carrot juice	UV-C and mild heat	UV: 3.92 J/mL, 3.6 min; heat: 60 °C	• UV-C and mild heat treatment could extend the shelf life of carrot juice up to 29 days, compared to the untreated that showed changes in quality from the 7th day	Gouma et al. (2020)
Carrot-orange juice	UV-C, mild heat (H), UV-C + H	UV-C light (UV-C, 1720 mJ/cm^2)	• The UV-C and mild heating process reported superior sensory quality than pasteurized juice	Carrillo et al. (2020)
Grape musts and wine	UV-C	30 min, 5.5 kJ/L, 2.3 J/cm^2	• UV-C developed no off-flavor in the treated wines	Golombek et al. (2021)
Grapefruit juice	UV-C + mild heat	39.6 J/L and 65 °C	• Combined treatment aids in longer microbial shelf stability and maintains the physicochemical properties of the juice during 28 days of storage at 4 °C	La Cava and Sgroppo (2019)
Grape juice	UV-C + addition of SO2	683 J/L (1 min), 1366 J/L (2 min), 68,349 J/L (10 min), 13,670 J/L (20 min)	• UV-C either low-dose (0.68 kJ/L and 1.37 kJ/L) or high-dose (6.83 kJ/L and 13.67 kJ/L) affected the sensory properties of grape juice	Czako et al. (2018)

Table 4 (continued)

Fruit juice samples	**Processing method**	**Treatment time and dose**	**Conclusive findings**	References
Fruits (cherry tomato, grape, apple, and pineapple)	UV-C and waterproof light-emitting diodes	275 nm	• Less visual changes of fresh-cut fruits compared to the control group • Hurdle technology extended the shelf life of fresh-cut fruits without adversely affecting quality parameters	Kim et al. (2021)
Rubi red grapefruit juice	UVC + Trans-CAH	UV-C (0, 10, and 20 min), trans-cinnamaldehyde (0, 25, and 50 g/mL)	• UV-C treated juice remained up to 9 days without any physicochemical or microbiological alterations	Ochoa-Velasco et al. (2018)
Lychee juice	UV-C	0–74.9 J/cm^2	• Based on microbiological shelf life, UV light might extend the shelf life of lychee juice by roughly 7 days when stored at 4 °C compared to the control sample	Visuthiwan and Assatarakul (2021)
Orange juice	UV-C and mild thermal treatment	19.75 J/L for 5 min, heated at 40 °C for 5 min	• UV-C-treated juice showed no significant difference of consumer acceptance compared to the fresh juice	Hernández-Carranza et al. (2021)
Red prickly pear juice	UV-C and pH	UV-C (0, 9.81, 15.13, and 31.87 mJ/cm^2) UV-C time: 15, 30, and 60 min, pH (3.6 and 7.0)	• UV-C light reduced chemical components such as betalains, total polyphenols, and antioxidant activity during storage	Mesta-Vicuña et al. (2022)
Pineapple juice	UV reactor equipped by a quartz glass sleeve	3.1 mW/cm^2, 2.5 and 19.86 mW/cm^2, 34.9 s	• UV was able to extend the shelf life of the pineapple juice for up to 5 weeks of storage	Mansor et al. (2017)

juice, according to sensory evaluation (Table 4) (Amanina et al., 2019). Sauceda-Gálvez et al. (2021) mentioned that UV-C + pressure homogenization resulted in no negative effects on sensorial qualities (i.e., taste, sweetness, sourness, freshness, and texture) of cloudy apple juice. In carrot juice, UV-C treated samples had better sensory characteristics compared to the thermally processed, as well as extended shelf life by 8 days (Riganakos et al., 2017).

A sensory analysis test confirmed that UV-C and mild thermal treatment of orange juice showed no significant difference on consumer acceptance compared to the fresh juice (Hernández-Carranza et al., 2021). The application of UV-C (100.47 kJ/L) *vs* UV-B reduced contamination and increased shelf life in apple and grape juices (Kim et al., 2021). Kinetic modeling of microbial degradation in lychee juice subjected to UV radiation (0–74.88 J/cm^2) showed that UV-treated (18.72 and 37.44 J/cm^2) samples extended the shelf life in juice approximately 7 days with no effects on pH, °Brix, titratable acidity, and antioxidant activity (Visuthiwan & Assatarakul, 2021). In carrot juice, UV-C and mild heat treatment could extend the shelf life up to 29 days (Gouma et al., 2020). The other study showed that UV-C and mild heat resulted in a superior sensory quality in carrot-orange juice than the pasteurized one (Carrillo et al., 2020). La Cava and Sgroppo (2019) demonstrated that the combined treatment of UV-C and mild heat helped in longer microbial shelf stability and maintained the physicochemical properties of the grapefruit juice during 28 days of storage at 4 °C. The combination of UVC + trans-cinnamaldehyde improved the shelf life in grapefruit juice without any physicochemical or microbial alterations (Ochoa-Velasco et al., 2018). Visuthiwan and Assatarakul (2021) reported that UV-C treatment extended the shelf life of lychee juice by 7 days when stored at 4 °C compared to the control sample. UV reactor equipped by a quartz glass sleeve extended the shelf life of the pineapple juice for up to 5 weeks during storage (Mansor et al., 2017).

The UV-C treatments (doses, 0.0–3.94 J/cm^2) enhanced the shelf life of grapefruit juice during storage at 4 and 10 °C, but ascorbic acid and antioxidant capacity (up to 30%) decreased especially when higher doses were applied (Ochoa-Velasco et al., 2018). The shelf life of lemon-melon mixed juice was extended to 30 days in UV irradiation compared to the control juice sample without any treatment which lasted only for 2 days (Fenoglio et al., 2020). Yıkmış et al. (2021) reported that UV-C and moderate heat treatment caused prolonged shelf life in apple juice. Yang et al. (2019) also confirmed that even using UV alone caused 3 weeks longer shelf life in apple juice. UV exposure at 14.2–99.4 mJ/cm^2 also showed only minor changes to the physical and chemical properties and sensory qualities of apple juice (Assatarakul et al., 2012).

From the studies in terms of sensory qualities and shelf life extension, it could be derived that combining UV treatment with other non-thermal technologies (hurdle concept) can enhance overall preservation while minimizing sensory changes. Additionally, proper product development and quality control procedures can help maintain the desired sensory attributes of the juice while ensuring safety and extended shelf life.

Conclusions and Future Perspectives

This review highlighted the impacts of hurdle technologies using UV irradiation on the physicochemical characteristics, microbial inactivation, and sensorial and shelf-life properties of fruit juices. Twenty distinct varieties of fruit juices were UV-processed, according to nearly 60 research papers. The most researched items in terms of using UV light processing to enhance safety, preserve overall quality, and extend shelf life were apple and orange juices. The application of UV irradiation alone or in conjunction with different non-thermal technologies was able to produce products with little to no enzyme and microbial activity thereby retaining fresh-like nutritional and sensorial quality. The combinations of UV and PEF, UV + mild heat, UV + ultrasonication, and many more showed synergistic effects on the inactivation of various microorganisms (e.g., *E. coli*, *Listeria monocytogenes*, S*almonella enteritidis*). However, hurdle technology using ultraviolet irradiation comes with its set of challenges and areas for future work. Future research on the cytotoxicity of various fruit juices utilizing the hurdle concept using UV irradiation is expected. Besides, combining UV irradiation with other non-thermal processing (hurdle technology) to achieve the desired shelf life and safety can be complex. Achieving the right balance and synergy in hurdle technologies can be a challenge. The other challenge could be scaling up for commercial production which may pose technical and economic challenges. Ensuring consistent results and cost-effectiveness on a larger scale can be difficult. It is also advisable to undertake studies on the energy demands of hurdle technologies to identify the optimal processing conditions. In conclusion, using UV to treat fruit juices in combination with other non-thermal processing (hurdle concept) is a potential alternative to conventional thermal treatments. However, more collaborations between food producers and the food chain are needed to conserve natural resources, food safety, and energy in different food processing phases.

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Data Availability The data used to support the findings of this study are included within the article.

Declarations

Ethical Approval Not applicable.

Competing Interests The authors declare no competing interests.

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