

A Review on Individual and Combination Technologies of UV-C Radiation and Ultrasound in Postharvest Handling of Fruits and Vegetables

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Date Submitted: 2021-05-26

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Record Type: Published Article

Submitted To: LAPSE (Living Archive for Process Systems Engineering)

Citation (overall record, always the latest version):

LAPSE:2021.0434

Citation (this specific file, latest version):

LAPSE:2021.0434-1

Citation (this specific file, this version):

LAPSE:2021.0434-1v1

DOI of Published Version: <https://doi.org/10.3390/pr8111433>

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Review

A Review on Individual and Combination Technologies of UV-C Radiation and Ultrasound in Postharvest Handling of Fruits and Vegetables

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Received: 24 September 2020; Accepted: 29 October 2020; Published: 10 November 2020



Abstract: Ultraviolet-C radiation and ultrasound technology are widely accepted and continuously being appraised as alternatives to conventional thermal techniques for decontamination of fruits and vegetables. However, studies in these areas have presented challenges related to quality, safety, limited capability, and cost of energy. This review paper presents an up-to-date summary of applications of ultraviolet-C radiation and ultrasound technology for postharvest handling of fruits and vegetables from relevant literature. The limitations associated with applications of ultraviolet-C radiation and ultrasound technology individually has prompted their combination alongside other antimicrobial strategies for enhanced bactericidal effect. The combination of ultraviolet-C radiation and ultrasound technology as a hurdle approach also provides enhanced efficiency, cost effectiveness, and reduced processing time without compromising quality. The review includes further scope of industrial-led collaboration and commercialization of ultraviolet-C radiation and ultrasound technology such as scale-up studies and process optimization.

Keywords: deterioration; cavitation; dosage; hurdle technology; microorganisms; nonthermal; decontamination

1. Introduction

Fruits and vegetables are an essential component of our diet and their consumption increases yearly due to perceived interest of consumers in healthy and functional foods [1,2]. However, they are susceptible to postharvest moisture loss, improper handling, mechanical damage, and microbial contamination. Postharvest moisture loss affects maturation, which can be inferred from evaluation of important quality parameters such as weight, texture, acidity, sugars, carotenoids, vitamins, and phenolic compounds. Microbial contamination is accompanied by postharvest losses and prevalence of foodborne disease outbreaks. Data suggest that about one-third of food (1.3 billion tons) fit for human consumption is wasted yearly, with 44% attributed to fruits and vegetables, while numerous foodborne illnesses and deaths linked to fresh produce contamination have been reported in the last two decades [3–6]. Food losses and wastes pose serious concern at a global level; hence, the United Nations agenda has initiatives with development investments towards preventing and reducing postharvest losses [6,7].

The common practices to reduce spoilage and enhance shelf life of fruits and vegetables include washing with sanitizers, refrigeration, controlled atmosphere storage using natural and synthetic preservative agents, and drying [8–14]. The majority of these approaches are marginally effective and may alter nutritional properties while the corrosive nature of some sanitizers has been linked with environmental and health concerns [15,16]. As consumer demands for minimally processed products with fresh-like characteristics has increased in recent times, this preoccupation has encouraged continuous evaluation of non-thermal technologies for postharvest handling of fruits and vegetables.

The non-thermal technologies of ultraviolet-C (UV-C) radiation and ultrasound (US) technology have been extensively studied for surface decontamination of fruits and vegetables, and are considered highly efficient, non-toxic, and environmentally friendly [17]. UV-C radiation is generated at wavelengths of 250–280 nm and is reported to disrupt functionality and integrity of microorganisms' DNA in addition to being linked with generation of reactive oxygen species that regulates physiological processes to induce secondary metabolite production [18]. On the other hand, US technology is a form of pressure waves beyond human hearing (>20 kHz), and high intensity US at low frequencies of 20–100 kHz can induce acoustic cavitation that generates reactive hydroxyl radicals associated with microbial inactivation and stimulation of secondary metabolite accumulation in fruits and vegetables [17,19,20].

Nevertheless, UV-C radiation can only penetrate up to several millimeters and US technology consumes high energy coupled with long treatment time, which limits their applications. This has encouraged the use of UV-C radiation and US technology in combination with other techniques for postharvest handling of fruits and vegetables with encouraging results [1,19,21–23]. The current review, drawn from selected past and current literature, presents research progress of the individual and combination approaches of UV-C radiation and US technologies in postharvest handling of fruits and vegetables. The types of disinfecting systems typically utilized for postharvest UV-C radiation and US technology decontamination of fruits and vegetables is also summarized. This review also included discussion on limitations associated with individual applications of UV-C radiation and US technology for postharvest decontamination of fruits and vegetables. The potential of a hurdle technology utilizing UV-C radiation and US technology in combination or simultaneously for maximizing and harnessing their advantages is also presented.

2. Applications of UV-C Radiation in Postharvest Handling of Fruits and Vegetables

2.1. Disinfecting Systems and Factors Affecting Efficiency

The use of UV-C radiation for food preservation was discovered in the 1930s, and the first studies on fruits and vegetables was recorded in 1977 when resveratrol and viniferins were induced in grape vine from UV-C exposure [24,25]. The efficacy of UV-C radiation for decontamination of fruits and vegetables is heavily dependent upon the type of disinfection systems, mode of applications, pulse intensity, morphology and location of microorganisms on fruits and vegetables, distance from irradiation source, and type of microorganism.

Typical systems for exposing fruits and vegetables to UV-C radiation consist of self-contained chambers with fluorescent germicidal lamps and have been widely reported in the literature. However, modifications to the conventional self-contained chambers have been reported to induce improved microbial reductions and maintain quality properties even at low UV-C radiation doses. For instance, Collazo et al. [23] showed that low doses of 0.1–0.3 kJ/m² from water-assisted UV-C radiation equipment with pressurized water sprinklers were enough to reduce respiration, maintain quality, and provoke 0.9–2.0 log CFU/g (log colony forming unit/g) reductions of *Listeria monocytogenes* (*L. monocytogenes*) and *Salmonella enterica* (*S. enterica*) in lettuce and spinach (Figure 1a). The study revealed that dual action of irradiation by immersion and simultaneous actions of process water from modification of the conventional treatment chambers with pressurized water sprinklers accounted for higher efficiency. Yan et al. [26] demonstrated that it is possible to reduce large variations and maximize UV-C radiation dose on fruit surfaces in disinfecting systems. In this study, conveyor belts were placed at

a distance of 14 cm from UV-C lamps to convey and rotate fruits between two treatment chambers connected by an inclined belt (Figure 1b). This inclusion to the conventional UV-C lamp self-contained chambers ensured dose uniformity such that fruits received an average dose of 1 kJ/m², compared with 0.2 kJ/m² received by fruits without rotation. The modified rotation device ensured 1.3–1.8 and 1.0–1.2 log CFU/fruit reductions in *Escherichia coli* O157:H7 (*E. coli* O157:H7) and *E. coli* ATCC 25922, respectively, compared with 0.5–0.7 log CFU/fruit reduction obtained without the rotation device, revealing the importance of dose uniformity for maximum effect of UV-C radiation in disinfection systems. Likewise, a benchtop UV-C radiation system that allowed upward and downward movement of fruits from a rotating roller was employed by Taze and Unluturk [27] to ensure uniformity of intensity (Figure 1c). They observed 3.0 and 2.38 log CFU/g reductions in total aerobic mesophilic bacteria and yeast and mold, respectively, at doses of 31.01 and 7.75 kJ/m², and reported that light intensity was almost constant at the lamp center and lower at both ends. Ensuring the uniformity of exposure on food surfaces due to the low penetrative ability of UV-C radiation is seen as the most important challenge to commercialization, and these studies have provided an avenue to ensure dose uniformity for maximum impact.

The applied dosage of UV-C radiation, the type of microorganism, and their location on fruits and vegetables have been reported to have significant effect on decontamination efficiency of UV-C radiation. Mukhopadhyay et al. [28] showed that increasing UV-C radiation doses from 0.6 to 6.0 kJ/m² resulted in 2.2–3.1 and 2.3–3.5 log CFU/fruit reductions, respectively, for cocktail mixtures of *S. enterica* and *E. coli* O157:H7 on the surfaces of tomato. Lower reductions of 1.9–2.8 and 1.7–3.2 log CFU/fruit, respectively, were recorded on the stem scar under the same conditions, indicating that specific location of microorganisms on produce may influence efficacy of treatment and should be considered during the design of UV-C radiation disinfection systems. Further analysis showed that color and texture of tomato were not affected by the increasing dosages. In contrast, Lim and Harrison [29] observed a reduction range of 3.22–4.39 log CFU/g in *S. enterica* for a dosage range of 0.223–1.785 kJ/m², irrespective of the contamination location on tomato placed in a close end reflector lined with aluminum foil. The high reduction from such low doses was attributed to the bacterial strain and low initial inoculum level utilized in the study, which corroborates the assertion that the sensitivity of bacteria to UV-C radiation may vary among species and strains of the same species.

The mode of application of UV-C radiation, pulse intensity, and distance of samples from irradiation source have also been reported to influence the actions of UV-C radiation during decontamination of fruits and vegetables. For example, short pulses of incident UV-C irradiance was not effective in reducing microbial population, which could be linked to ability of resistant strains of microorganism to produce protein protection mechanism against UV-C radiation treatment, especially at short treatment duration [30]. The study showed that there was no significant difference in log reductions (1.0 log CFU/g) of resistant strains of *Enterococcus faecalis* on zucchini squashes when a UV-C radiation system was operated in continuous incidence radiation of 0.011 kJ/m² or pulse irradiation of 0.067 kJ/m² in a discontinuous fluence. In addition, a continuous UV-C incidence radiation of 0.011 kJ/m² for 90 s did not have any significant effect on the reduction of *Deinococcus radiodurans* on zucchini squashes. However, higher inactivation of *E. coli* was reported on tomatoes and lettuce when the intensity of UV-C radiation was increased from 6.5 to 16 W/m² in a treatment cabinet [31]. Enhanced reductions of 2.8 and 1.7 log CFU/g were also observed in tomatoes and lettuce, respectively, for samples closer to the radiation source at 31 cm compared with samples placed at a distance of 70 cm. In the same vein, Cote et al. [32] observed that increasing intensity for a given dose could maximize the benefits of UV-C radiation. For an applied dosage of 4 kJ/m², only 5% of tomatoes irradiated with higher intensity of 33 W/m² showed incidences of postharvest rot caused by *Botrytis*, compared with 8% from lower intensity of 3 W/m², after 9 days of storage. On the other hand, 12% of strawberries irradiated with higher intensity showed decay symptoms after 5 days, compared with 46% of strawberries irradiated with lower intensity. The treatment also delayed ripening and maintained better quality of the fruits, while titratable acidity, soluble solids, and antioxidants properties were unaffected.

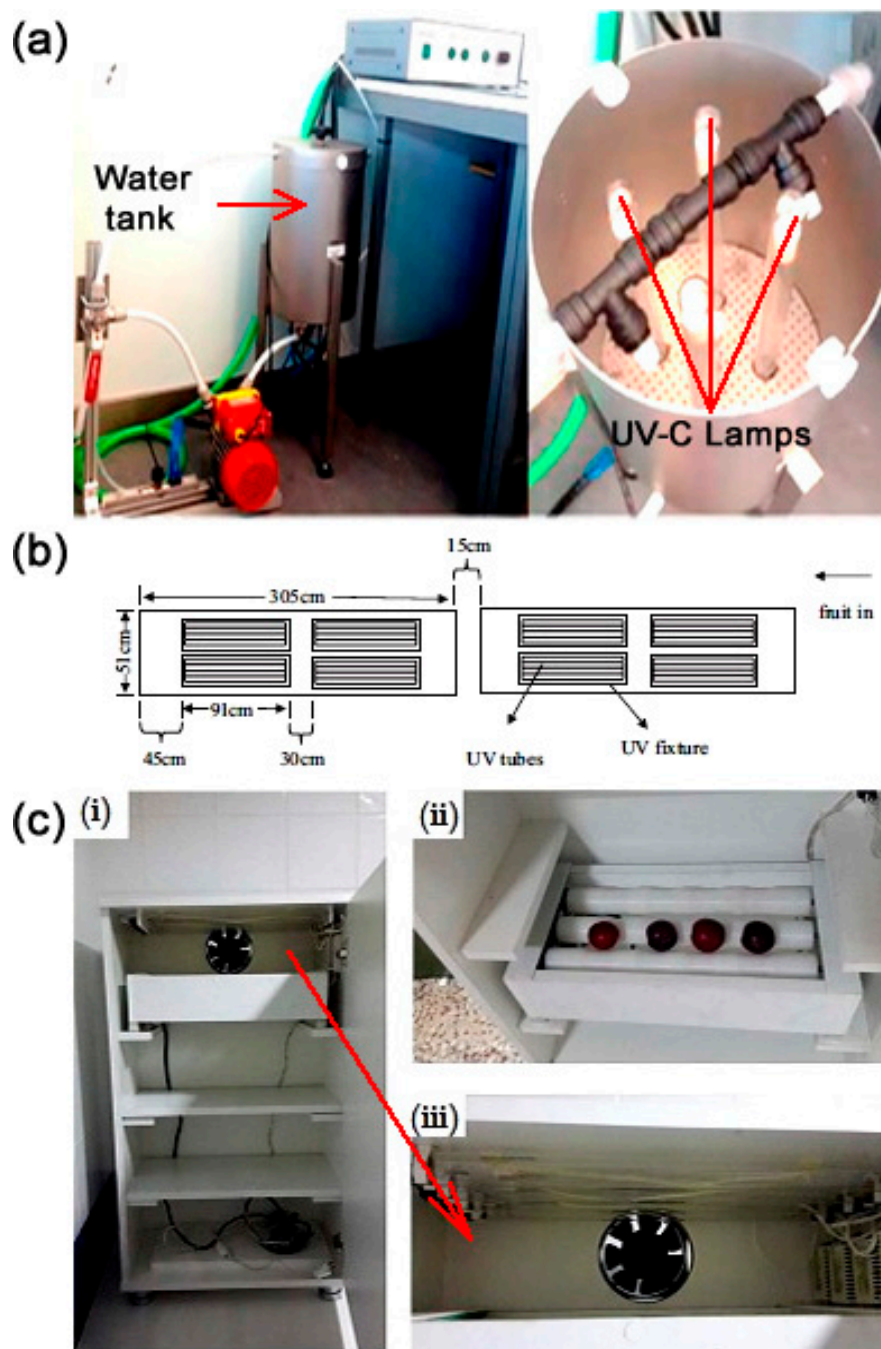


Figure 1. Disinfecting systems for UV-C radiation decontamination of fruits and vegetables. (a) Water-assisted UV-C set-up. Reproduced with permission from Collazo et al., *International Journal of Food Microbiology*; published by Elsevier, 2019. (b) Schematic diagram of a commercial UV-C treatment chamber. Reproduced with permission from Yan et al., *Postharvest Biology and Technology*; published by Elsevier, 2014. (c) Benchtop UV-C set-up with (i) tray system, (ii) rotating roller bearing, and (iii) UV-C lamps and cooling system. Reproduced with permission from Taze and Unluturk, *Scientia Horticulturae*; published by Elsevier, 2018.

The influence of fruit surface characteristics on the inactivation efficiency of UV-C radiation has also been studied, with results demonstrating that microorganisms on fruits' surfaces responded differently to UV-C radiation [33]. It was observed that microbial inactivation was lower for fruits with rougher surfaces (strawberry, cantaloupe, and raspberry) compared to less hydrophobic fruits with smoother surfaces (pear and apple). Reductions of 2.9 and 2.1 log CFU/g were recorded for

E. coli O157:H7 on apple and pear surfaces, respectively, at 0.9 kJ/m² for 60 s compared with 2.0 and 1.1 log CFU/g recorded for strawberry and raspberry at 7.2 and 10.5 kJ/m² for 480 and 720 s, respectively. On the other hand, *L. monocytogenes* showed more resistance than *E. coli* O157:H7, revealing 1.6 and 1.7 log CFU/g reductions, respectively, on apple and pear at 3.75 kJ/m² and 11.9 kJ/m². The log reduction of *L. monocytogenes* was 1.0 log CFU/g on both cantaloupe and strawberry at 11.9 kJ/m². The findings from this study were corroborated by Syamaladevi et al. [34] by using a similar device when they observed that trichomes on peach surfaces and wounds on pears protected and shielded microorganisms from irradiation, while smaller surface roughness and spreading coefficient of pear surfaces compared with peach likely caused a more uniform distribution of microbial cells on pear surfaces. Maximum reductions of 3.70 log CFU/g were recorded for *E. coli* on intact pear surfaces, with lower reductions of 3.10 and 2.91 log CFU/g achieved on wounded pear and peach surfaces, respectively, after 4 min at 7.56 kJ/m².

2.2. Effects of UV-C Radiation on Microorganism Inactivation and Quality of Fruits and Vegetables

Table 1 lists studies that have used UV-C radiation to inactivate microorganisms and subsequent effects on quality parameters for a wide variety of fruits and vegetables. Collectively, these studies demonstrate the potential of UV-C radiation at low doses of 0.00176–1 kJ/m² for enhancing bioactive compound production, reducing enzymatic activities, extending shelf life, and having degradative effects on biological process-regulating proteins responsible for deteriorative changes of postharvest produce [33,35–39]. The range of doses were also responsible for 1.2–2.9 log CFU/g reduction in *E. coli* O157:H7, *Salmonella* spp., and *Listeria* spp., as well as reduced rot and decay development. In contrast, Wang et al. [40] observed that a low dose of 0.3 kJ/m² had no effect on total bacteria number and browning-related enzymes of fresh cut lotus during storage, and resulted in a high degree of browning, but the authors maintained that a moderate dose of 1.5–3 kJ/m² significantly retarded microbial growth and suppressed the activities of browning-related enzymes. Pinheiro et al. [41] also reported that low doses of 0.97 kJ/m² was not adequate for metabolic degradation delay in tomatoes but presented 2.1 log CFU/g reduction in mesophilic load, delayed red color development, and caused increases in firmness and phenolic content. The variations in results could be attributed to the factors discussed earlier, in addition to the type of disinfection systems used.

It is apparent that increasing dosage applications could result in increased microbial reduction. For instance, Sommers et al. [42] observed a progressive increase from 2.59 to 3.79 log CFU/g in the inactivation of *L. monocytogenes*, *Salmonella* spp., and *Staphylococcus aureus* (*S. aureus*) on Roma tomatoes and jalapeño peppers when the dosage was increased from 5 to 40 kJ/m². Similarly, successive increases in UV-C radiation doses evoked greater reductions of *E. coli*, *S. aureus*, *S. Enteritidis*, and *Listeria innocua* (*L. innocua*) on tomato, lettuce, and strawberry, with no modifications in texture and appearance [19,43]. Doubling UV-C radiation dose from 32 to 72 kJ/m² also doubled the reduction of human adenoviruses from 0.92 to 2.22 and 1.26 to 3.98 logs for tomato and strawberry, respectively.

Table 1. List of fruits and vegetables treated with UV-C radiation

Fruit/ Vegetable	UV-C Parameters	Main Findings		Sources
		Quality Improvement Attributes	Microbial Log Reduction and Disease Incidence	
Apple	7.5 kJ/m ² + blanching 1.0 kJ/m ²	Retained color	<i>L. innocua</i> , <i>E. coli</i> , <i>Saccharomyces cerevisiae</i> : 1–1.19 <i>E. coli</i> : 1.89, <i>L. innocua</i> , <i>S. enterica</i> : 1.5	[44] [38]
	0.92–5 kJ/m ² , 60–300 s	Retained color and physicochemical properties	<i>E. coli</i> : 2.9, <i>L. monocytogenes</i> : 1.6	[33]
Apricot	0.74 kJ/m ² , 10 s	-	<i>E. coli</i> : 1.2, <i>Salmonella</i> spp.: 1.5	[37]
	1.0–2.54 kJ/m ²	-	<i>E. coli</i> O157:H7: 0.5–1.8	[26]
	7.75 kJ/m ²	-	Yeast and mold: 2.38, TAPC: 3.0	[27]
Blueberry	2 kJ/m ² , 600 s	Increased anthocyanin, phenols, and antioxidants	<i>Colletotrichum acutatum</i> : 10% reduction	[45]
	9.54 kJ/km ² , 120 s, + O ₃ , 60 s		<i>E. coli</i> : 3.08–3.8	[46]
Broccoli	2.5–7.5 kJ/m ² , + 100 mg/L NEW + MAP + PA	Retained total phenols and antioxidants; increased enzyme activity, reduced steric and α -linolenic acid	<i>L. monocytogenes</i> : 0.72, <i>E. coli</i> , <i>S. Enteritidis</i> : 1.22–3.0, psychrophilic bacteria: 1.3	[11,47]
Carrot	0.78 kJ/m ²	Increased bioactive compounds and whiteness index; reduced enzyme activity and O ₂ /CO ₂ rate	Aerobic mesophile: 1.7	[36]
	57.6 kJ/m ² , 3600 s	Increased enzyme reaction and whiteness index	-	[31]
Cauliflower	5 kJ/m ² , 30 s + AMF		<i>L. monocytogenes</i> : 1.5, <i>E. coli</i> : 2.0, yeast and mold: 2.0	[13]
Date palm	6.22 kJ/m ² , + O ₃	Increased antioxidants and TA; reduced sugar and water activity	Yeast and mold: 1.63, coliform: 0.82, mesophilic counts: 1.05	[48]
Grape	6 kJ/m ² , + 0.5% chitosan	Increased resveratrol, reduced respiration, weight loss	<i>Botrytis cinerea</i> : growth inhibition	[49]
Lettuce	57.6 kJ/m ² , 3600 s	Overall quality parameters maintained	<i>E. coli</i> : 1.7	[31]
	24–72 kJ/m ² , 1200–3600 s		<i>E. coli</i> : 1.75, <i>L. innocua</i> : 1.27, <i>S. aureus</i> : 1.21, <i>S. Enteritidis</i> : 1.39, HAdV: 2.13	[19,43]
	0.1–0.5 kJ/m ² , 60–300 s, PA + MAP	Oxidative discoloration, enhanced respiration	<i>L. monocytogenes</i> : 1.2–2.1, MAM: 1.3, <i>S. enterica</i> : 1.8–2.5	[23]

Table 1. Cont.

Fruit/ Vegetable	UV-C Parameters	Main Findings		Sources
		Quality Improvement Attributes	Microbial Log Reduction and Disease Incidence	
Lotus root (fresh cut)	0.3–12 kJ/m ² , 60–2400 s	Low browning degree and soluble quinone content; inactivation of PAL, POD, TSS; hardness maintained	Total bacteria: 1.0–1.4	[40]
Mango	0.00176–0.00706 kJ/m ² , 900–1800 s 5 kJ/m ²	Increased flavonoid and antioxidant activity	Microbial load under acceptable limit	[39]
		-	<i>E. coli</i> : 1.98, <i>Cronobacter sakazakii</i> : 2.60	[50]
Melons	11.9 kJ/m ² , 840 s 1.2 kJ/m ² , 60 s 2.8 kJ/m ²	-	<i>L. monocytogenes</i> : 1.0	[33]
		Retained physicochemical properties Color, lycopene, vitamin C preserved	TVC: 2.16, <i>Enterobacteriaceae</i> : 2.62	[51]
		-	<i>Enterobacteria</i> , AMB, APB: 2.0	[52]
Peach	4 kJ/m ² , 120 s	-	<i>E. coli</i> : 2.5	[34]
Pear	1.7–4 kJ/m ² , 90–180 s 0.92–11.9 kJ/m ² , 60–840 s 87 kJ/m ² , 1200 s 7.5 kJ/m ²	Maintained weight, TSS, and texture	<i>Penicillium expansum</i> : 2.7–2.8, <i>E. coli</i> : 2.6–3.59	[34,53]
		-	<i>E. coli</i> : 2.1, <i>L. monocytogenes</i> : 1.7	[33]
		-	<i>L. monocytogenes</i> , <i>E. coli</i> : 2.6–3.4	[54]
		Increased firmness; color, TA, and TSS maintained	<i>E. coli</i> : 3.2, <i>L. innocua</i> : 2.9, <i>S. enterica</i> : 2.8	[55]
Pepper	5–40 kJ/m ² 1.483 kJ/m ² , 120 s	-	<i>S. aureus</i> : 3.09–3.73, <i>L. monocytogenes</i> : 3.11–3.72	[42]
		Improved firmness; color preserved	<i>L. innocua</i> : 1.05	[56]
Pineapple	0.2–4.8 kJ/m ² + PET pouches	Maintained quality and color	LAB, yeast and mold: 0.20–2.0, <i>Enterobacteriaceae</i> : undetected	[57]
Plum	10 kJ/m ² + ClO ₂ + fumaric acid	-	<i>E. coli</i> : 2.07–5.48, <i>L. monocytogenes</i> : 1.62–6.26	[58]
Pomegranate	1.13 kJ/m ² , + MAP	Anthocyanin; antioxidant activity maintained	LAB, AMB, <i>Enterobacteriaceae</i> : reduced growth	[59]
Raspberry	7.2 kJ/m ² , 480 s	-	<i>E. coli</i> : 1.0	[33]
Spinach	4.54 kJ/m ² 0.212–0.848 kJ/m ² , + ClO ₂ 0.1–0.5 kJ/m ² , 60–300 s, PA + MAP	Chlorophyll maintained; low ethylene production	Mesophilic, psychrophilic, coliform, enterobacteria: 1.1	[60]
		Color and texture maintained	<i>E. coli</i> : 2.01–5.17, <i>Salmonella</i> Typhimurium: 2.10–5.47, <i>L. monocytogenes</i> : 1.70–4.32	[16]
		Reduced respiration; maintained quality	<i>L. monocytogenes</i> : 0.5–2.2, MAM: 1.3, <i>S. enterica</i> : 0.8–2.0	[23]

Table 1. Cont.

Fruit/ Vegetable	UV-C Parameters	Main Findings		Sources
		Quality Improvement Attributes	Microbial Log Reduction and Disease Incidence	
Strawberry	0.5 kJ/m ²	Increased PAL and ethylene production	<i>B. cinera</i> , <i>Rhizopus stolonifera</i> , <i>Mucor</i> sp.: reduced incidence	[35]
	0.92–11.9 kJ/m ² , 60–840 s	-	<i>E. coli</i> : 2.0, <i>L. monocytogenes</i> : 1.0	[33]
	24–72 kJ/m ² , 1200–3600 s	-	<i>E. coli</i> , <i>S. aureus</i> , <i>S. Enteritidis</i> , <i>L. innocua</i> : 1–1.4, HAdV: 2.85–3.98	[19,43]
	3, 33 W/m ² , 4 kJ/m ²	Low weight loss and respiration rate; increased anthocyanin	<i>Botrytis cinera</i> : reduced incidence	[32]
	1.483 kJ/m ² , 120 s	Improved firmness; anthocyanin retained	Total mesophiles: 0.26	[56]
Tomato	5–40 kJ/m ²	-	<i>S. aureus</i> : 3.13–3.63, <i>Salmonella</i> spp.: 3.02–3.79, <i>L. monocytogenes</i> : 2.59–3.60	[42]
	0.97 kJ/m ² , 180 s	Low weight loss; improved firmness and phenolic content	Total microbial count: 0.6–2.1	[41]
	0.6–6.0 kJ/m ² , 10–100 s	Firmness and color maintained	<i>E. coli</i> : 2.3–3.5, <i>S. enterica</i> : 2.2–3.1	[28]
	57.6 kJ/m ² , 3600 s	Increase in tomato color index	<i>E. coli</i> : 2.8	[31]
	2 kJ/m ² , 500 s + MAP	Increased lycopenes; color maintained	<i>S. Typhimurium</i> : 1.3	[61]
	3, 33 W/m ² , 4 kJ/m ² , 120 s	Low weight loss and respiration rate; bioactive and physicochemical content retained	<i>B. cinerea</i> : reduced incidence	[32]
	3 kJ/m ²	Higher total phenol and firmness; reduced ethylene production and enzyme activity	Decrease in decay severity	[62]
	0.223–1.785 kJ/m ²	Color and texture maintained	<i>S. enterica</i> : 3.22–4.39	[29]
0.848 kJ/m ² , + ClO ₂	-	<i>E. coli</i> : 2.27, <i>S. Typhimurium</i> : 2.20, <i>L. monocytogenes</i> : 1.66	[16]	
Watercress	1.483 kJ/m ² , 120 s	Improved firmness; color maintained	Total coliforms: 0.53	[56]

TAPC: total aerobic plate count, NEW: neutral electrolyzed water, MAP: modified atmosphere packaging, PA: peroxyacetic acid, AMF: antimicrobial formulations, TA: titratable acidity, HAdV: human adenovirus, MAM: mesophilic aerobic microbes, PAL: phenylalanine, POD: peroxidase, TSS: total soluble solids, LAB: lactic acid bacteria, AMB: aerobic mesophilic bacteria, APB: aerobic psychrotrophic bacteria.

The synergistic or additive effects of combining UV-C radiation with other techniques for improved efficiency have also been studied. Enhanced reductions of 3 log CFU/g were recorded in the populations of *E. coli* and *S. Enteritidis* when UV-C radiation was combined with either neutral electrolyzed water or peroxyacetic acid for broccoli decontamination, compared with 1.3–2.2 log CFU/g obtained for individual application of UV-C radiation at 7.5 kJ/m² [11,47]. Combination treatment also maintained quality, retained bioactive and fatty acid contents, and was seen as a potential eco-friendly alternative to conventional NaClO application. Similar enhanced reductions in *E. coli* on blueberry, and *L. monocytogenes*, *E. coli*, and yeast and mold on cauliflower were also reported when low UV-C doses were combined with ozone and antimicrobial formulations [13,46]. The effects of combining UV-C radiation and ClO₂ gas was also observed to be significantly greater than the sum of individual inactivation for the decontamination of spinach and tomato [16]. Individual UV-C radiation application at 0.848 kJ/m² reduced *E. coli* O157:H7 and *Salmonella* Typhimurium by 1.85 and 2.02 log CFU/g, respectively, while combined treatment reduced the population by 5.17 and 5.41 log CFU/g on spinach and 5.62 and 5.46 log CFU/g on tomato. Enhanced microbial reduction was attributed to cell membrane damage and changes to membrane permeability as a result of the synergistic actions of UV-C radiation and ClO₂ gas. This position was also maintained by Kim and Song [58] during the sequential application of ClO₂ gas and UV-C radiation on plum. The synergistic effect produced 4 and 3.27 log CFU/g reductions in *L. monocytogenes* and *E. coli* O157:H7, respectively, compared with 1.62 and 2.07 log CFU/g reductions obtained for individual UV-C radiation application. The authors however upheld that sequential applications of ClO₂ gas, UV-C radiation, and fumaric acid, which produced 5.48 and 6.26 log CFU/g reductions, respectively, in *E. coli* O157:H7 and *L. monocytogenes*, was the most effective combination treatment.

3. Applications of US Technology in Postharvest Handling of Fruits and Vegetables

3.1. Disinfecting Systems and Factors Affecting Efficiency

The antimicrobial effect of US technology was first documented 80 years ago, but its prospective practical application for microbial inactivation began in the 1960s [63]. The chemical reactivity of a system is affected by US technology through actions of cavitation and sonolysis from mechanical vibrations, typically produced from transformation of high-frequency electrical energy by piezoelectric transducers in probe or tank systems [15,19]. The threshold of cavitation bubble in the tank or probe systems is usually influenced by US frequency, power, intensity, and exposure time. The sonochemist typically uses frequencies of 20–50 kHz, as it is easier to obtain cavitation at these frequencies [64]. Together with the type of microorganism, mode of application in terms of pulse or continuous modes, and dual-mode or mono-mode frequency, these factors affect the efficiency of US technology during decontamination of fruits and vegetables.

For the US probe systems, a pulse mode application of 10 s on and 5 s off from a 15 mm diameter, 20 kHz, 400 W, and 226 W/cm² probe system submerged in water (Figure 2a) was capable of reducing initial total number of colonies and yeast and mold on cucumber by 0.49–1.02 and 0.41–0.84 log CFU/g, respectively, with increasing treatment time from 5 to 15 min under modified atmosphere packaging storage [65]. Treatment up to 10 min effectively reduced losses of firmness, ascorbic acid, color, soluble solids, and weight, and maintained cell wall integrity. Further increase in treatment time led to deterioration of quality properties. Similarly, Millan-Sango et al. [66] reported 2.56 log CFU/cm² reduction in *E. coli* O157:H7 on lettuce leaves at pulse mode application of 10 s on and 6 s off from a 14 mm probe, 26 kHz, 90 μm, and 200 W US system operating in both continuous and pulsed mode configurations. Results showed no significant differences between continuous and pulsed mode applications for up to 25 min of application, suggesting that decontamination efficacy was dependent upon treatment time rather than the configuration of the probe system utilized.

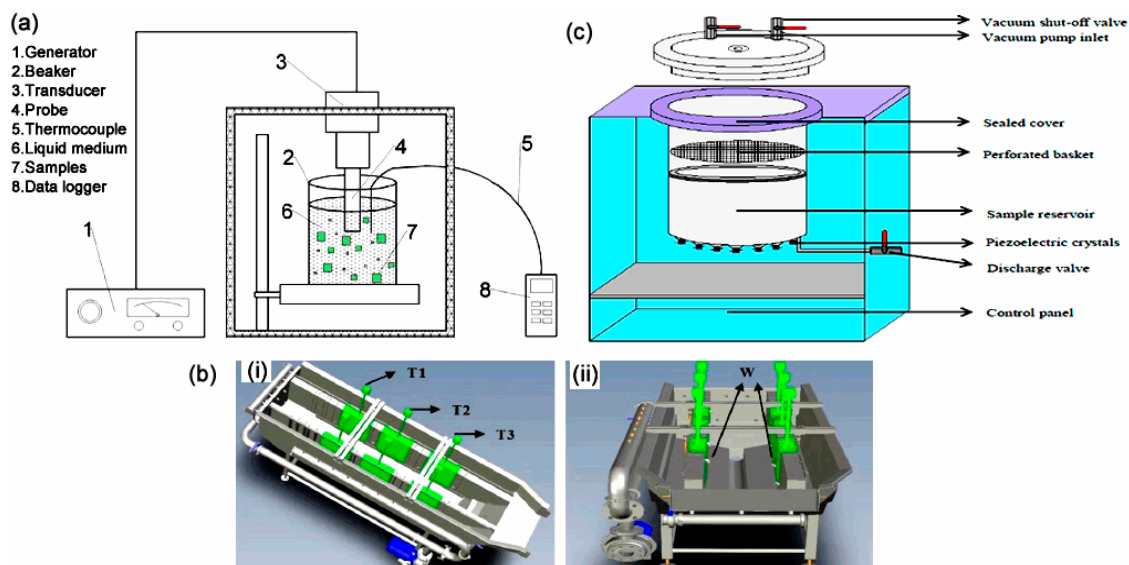


Figure 2. Typical disinfecting systems for ultrasound (US) technology decontamination of fruits and vegetables. (a) Schematic representation of US probe system. Reproduced with permission from Fan et al., *Ultrasonics Sonochemistry*; published by Elsevier, 2019. (b) Schematic diagram of US vacuum impregnation system. Reproduced with permission from Yilmaz and Bilek, *Ultrasonics Sonochemistry*; published by Elsevier, 2018. (c) Continuous-flow US bath equipment depicting (i) different transducers T1, T2, and T3, and (ii) washing area, W. Reproduced with permission from Zhou et al., *Innovative Food Science and Emerging Technologies*; published by Elsevier, 2012.

Increasing US intensity in a probe system has also been reportedly associated with enhanced antimicrobial activities while higher intensities had negative effects on product quality during storage. For example, reduced decay incidence of gray mold on strawberry with increasing intensity from 10.6–31.8 W/cm² was reported by Aday et al. [67] from a 1.9 cm diameter probe system operating at 20 kHz. Results also show that pH, color, soluble solids, and sugar content of strawberry treated with 10.6–21.2 W/cm² were better when compared with those treated with 31.8 W/cm², indicating that higher US intensity was detrimental to the quality of strawberry. In the same vein, Wang et al. [68] showed that the population of total bacteria and yeast and mold on tomato reduced to a range of 0.42–1.04 and 0.41–0.93 log CFU/g, respectively, with increasing US intensity from 66.64 to 145.74 W/L. Likewise, lower intensity levels inhibited ethylene production and respiration rates, and maintained firmness and antioxidant properties, while higher intensity had negative effects on tomato quality, demonstrating that appropriate US intensity can inhibit decay and maintain nutritional properties and flavor of tomato during storage.

For the US bath systems, research has demonstrated that it is more challenging to obtain cavitation at higher frequencies, with US penetration inversely proportional to frequency, while dual-mode frequency can be associated with improved cavitation when compared with mono-mode frequency applications. In this manner, Zhou et al. [63] fabricated a closed-tank continuous-flow system that allowed for frequency and nominal power variation and observed that 25, 40, and 75 kHz transducers dissipated 95, 85, and 45% rated power, corresponding to intensities of 79.41, 68.95, and 42.36 W/L, respectively (Figure 2b). The use of agitation ensured spatial uniformity of US treatment, and the populations of *E. coli* O157:H7 on spinach leaves were reduced by 4.45, 4.21, and 2.42 log CFU/g, respectively, from 25, 40, and 75 kHz transducers, suggesting that non-uniform cavitation from ultrasonic field variations may contribute to variations in microbial inactivation and cross-contamination in the US bath system. In a recent study, Mustapha et al. [20] showed that the application of dual-mode frequency of 20/40 kHz during US treatment of tomato presented higher microbial reductions of 1.3–2.6 log CFU/g for mesophilic bacteria and molds and yeasts, compared with <1 log CFU/g obtained when mono-mode frequency of 20 or 40 kHz was applied. There were no

detrimental effects on the bioactive compounds and physicochemical properties of tomato during storage, substantiating the enhanced cavitation characterized by dual-mode frequency applications.

It has also been demonstrated that substances can be incorporated into samples from the US bath system for better effects. Yilmaz and Bilek [69] combined vacuum impregnation and US (72–840 W, 35 kHz) in custom-made equipment, observing that calcium and black carrot phenolics can be incorporated into apple tissues to produce natural colorant-fortified products without disturbing cellular integrity (Figure 2c). Treatment reduced psychrophilic and mesophilic bacteria on apples by 1.0–2.6 log CFU/g during storage and led to increases in firmness and bioactive compounds, while higher power levels resulted in apple cell rupture, which was evident from increased ion leakage in apple tissues. Wiktor et al. [70] showed that immersion treatment from a 40 kHz, 180 W bath system presented apples with lower mass loss of 0.5–1.2%, dry matter of 0.115 kg dm/kg, higher bioactive compound contents, and less color change when compared with contact treatment from a 24 kHz, 100% amplitude ring sonotrode probe system. The surrounding water during immersion treatment played a significant role in water gain and cooling of apples, hence lower weight loss, while localized oxygen on apple tissue pores and enhanced enzymatic activities during contact treatment could degrade bioactive compounds. Although this may appear to suggest that treatment using the US bath system has shown a better quality of sample properties when compared with the US probe system, this does however need more detailed and careful comparison in terms of same usage of US energy frequency and intensity.

3.2. Effects of US Technology on Microorganism Inactivation and Quality of Fruits and Vegetables

Table 2 presents a summary of some studies that have applied US technology to inactivate microorganisms and subsequent effects on quality parameters for a number of fruits and vegetables. The majority of the applications were carried out in combination with sanitizers so as to avoid possible cross-contamination, since microorganisms are usually released into the wash water during US decontamination. However, among the individual US applications, Gani et al. [71] reported 2.0 and 1.2 log reductions in bacterial counts and yeast and mold, respectively, in addition to retention in color, firmness, vitamin C, and antioxidant activity. Prolonged exposure time after 40 min, 33 kHz, and 60 W did not further extend shelf life but may have caused injuries to strawberry samples. In another study, the action of US at 25 kHz and 26 W/L was reported as similar to the actions of abiotic stress such as wounding in triggering and eliciting defense systems in Romaine lettuce [72]. A response mechanism was suggested for such actions (Figure 3a), and treated lettuce displayed enhanced antioxidant activity, higher firmness, delayed enzymatic browning, and absence of deterioration during storage. Preservative treatments are usually known to be associated with the degradation of important freshness-related attributes that define the quality of fresh produce. This perception needs to be critically considered, especially the effects on health-stimulating phytonutrients and other related compounds during the design and selection of processing parameters.

For combination applications, the synergistic effects of US and chemical sanitizers, surfactants, organic acids, and electrolyzed water for improved decontamination efficiency and enhanced quality attributes have been reported [10,73–84]. Increased efficiency was observed without synergistic effect, and also with both synergistic and antagonistic effects in some cases. Park et al. [79] reported antagonistic effects against *Cronobacter sakazakii* when US at 37 kHz and 380 W was combined with 150 ppm of NaOCl. Although the plausible reason for antagonistic effect was not clear, synergistic combination mostly eliminated bacteria cells from the surface of lettuce and in the stomata, as observed in the scanning emission spectroscopy (Figure 3b), yielding 4.44 log CFU/g reduction of *C. sakazakii* compared with 0.01–2.71 log CFU/g reduction for individual applications of US and NaOCl. These studies demonstrated that US alone was not greatly effective, even with long treatment time, while the cavitation effect of US detached microorganisms from fresh produce, especially at inaccessible regions, increasing their susceptibility to sanitizers. Thus, the chemical composition of the liquid in the US system can influence decontamination actions. The US system also promoted the rapid dispersion

of organic matter, which increased their contact time with sanitizer constituents, leading to minimal residues in post-treatment solutions. The presence of microorganisms in treatment solutions were also very low and, in some cases, nonexistent, indicating that US and adequate sanitizer concentrations could prevent and/or reduce cross-contamination.

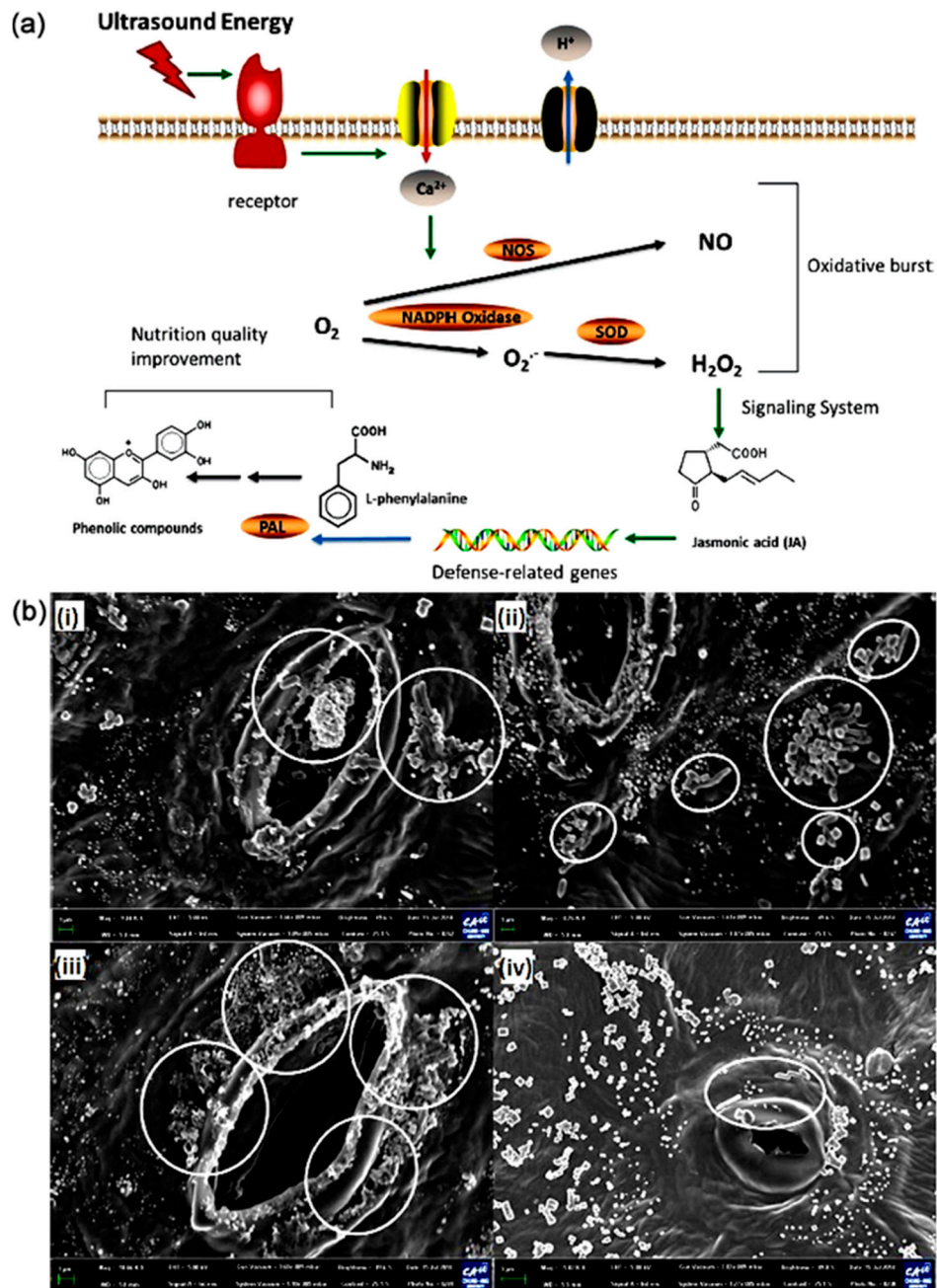


Figure 3. (a) Proposed mechanism of secondary metabolism response in Romaine lettuce during US. Reproduced with permission from Yu et al., Food and Bioprocess Technology; published by Springer Nature, 2016. (b) Field emission scanning electron microscopy of lettuce head showing aggregation and elimination of *Cronobacter sakazakii* during treatment: (i) control, (ii) US treatment, (iii) NaOCl treatment, and (iv) combined US and NaOCl treatment. Reproduced with permission from Park et al., Food Control; published by Elsevier, 2016.

Table 2. List of fruits and vegetables treated with US technology.

Fruit/ Vegetable	Ultrasound Parameters	Main Findings		Sources
		Quality Attributes	Microbial Log Reduction and Disease Incidence	
Apple	170 kHz, + 20 ppm ClO ₂ , 360 s	-	<i>E. coli</i> : 3.3, <i>S. enterica</i> : 4.0.	[73]
	40 kHz, 180 W	Higher antioxidant and phenolic content	-	[70]
	35 kHz, 72–840 W, + VI	Increases in bioactive compounds, calcium, and ion leakage	Psychrophilic and mesophilic bacteria: 1.0–2.6	[69]
Asparagus	40 kHz, 360 W, +2% acetic acid +50 mg/kg gibberellic acid	Low weight loss; increased soluble solids, phenols, ascorbic acid, and chlorophyll; inhibited PAL and POD	Yeast and mold, total number of colonies: 2	[85]
Cabbage	32 kHz, 10 W/L, 600 s + surfactant	-	<i>E. coli</i> : 2.91	[74]
	40 kHz, 400 W/L, 180 s, +40 °C + SAEW + wash water	Overall visual quality, browning, and off-odor under acceptable limits	Yeast and mold: 2.5–3.24, <i>E. coli</i> : 2.6–3.32, total bacteria count: 2.54–3.97, <i>L. monocytogenes</i> : 2.8–3.11, <i>Enterobacteriaceae</i> : 3.66	[75,86,87]
Cucumber	37 kHz, 13.57 W/L, + PA	Color, moisture content, and texture maintained	<i>C. sakazakii</i> : 0.60, 3.51	[76]
	20 kHz, 400 W, 226 W/cm ² , 300–600 s	Improved cell wall integrity; retained ascorbic acid; reduction in weight loss, firmness, and soluble solids	Yeast and mold: 0.41–0.84, total number of colonies: 0.49–1.02	[65]
Kiwifruit	30 kHz, 368 W/cm ² , + NaOCl	Reduced vitamin C, soluble solids, and firmness	Total bacteria count: 2.35, yeast and mold: 1.36	[88]
	40 kHz, 350 W, 600 s + nano-ZnO coating + MAP	Improved texture; low CO ₂ and ethylene production	-	[89]
Lettuce	32 kHz, 10 W/L, 600 s + surfactant	-	<i>S. Typhimurium</i> : 2.7, <i>E. coli</i> : 2.11	[74]
	40 kHz, 400 W/L, 180 s, + SAEW + wash water	-	Yeast and mold: 2.25, total bacteria count: 2.6, <i>E. coli</i> : 2.5–2.8, <i>L. monocytogenes</i> : 2.6	[75]
	40 kHz, 30 W/L, 300 s, + organic acids	Maintained color and textural properties	<i>E. coli</i> : 2.75, <i>S. Typhimurium</i> : 3.18, <i>L. monocytogenes</i> : 2.87	[77]
	37 kHz, 30 W/L, 3600 s, + BPW + 24 kJ/m ² , 1200 s	-	<i>E. coli</i> : 2.3, <i>S. aureus</i> : 1.7, <i>S. Enteritidis</i> : 5.72, <i>L. innocua</i> : 1.88, HAdV: 1.75–2.85	[19,43]
	26 kHz, 200 W, 90 µm + essential oils	Increased electrolyte leakage	<i>S. enterica</i> : 1.68–3.08, <i>E. coli</i> : 0.76–2.65	[15,66]
	25 kHz, 26 W/L, 60 s	Delayed browning; enhanced bioactive content	-	[72]
	42 kHz, 0.5 W/ml, + Cl ₂ + surfactants	Higher values of color change and electrolyte leakage	<i>E. coli</i> : 2.61, <i>L. innocua</i> : 2.23, <i>P. fluorescens</i> : 1.10–2.10	[78]
	37 kHz, 13.57 W/L, + NaClO	pH and sugar content maintained	<i>C. sakazakii</i> : 0.58–4.44	[79]
20 kHz, 131.25 W/L + NNEW	-	<i>E. coli</i> : 4.4, <i>S. Typhimurium</i> : 4.3	[80]	

Table 2. Cont.

Fruit/ Vegetable	Ultrasound Parameters	Main Findings		Sources
		Quality Attributes	Microbial Log Reduction and Disease Incidence	
Melons	40 kHz, 120 s, + 1% lactic acid	-	<i>E. coli</i> : 2.5, <i>S. enterica</i> Enteritidis: 3.1	[81]
Parsley	32 kHz, 10 W/L, 600 s + surfactant	-	<i>E. coli</i> : 0.84	[74]
Peach	40 kHz, 600 s, 8.8 W/L + SA	Higher phenol content and enzyme activities	<i>P. expansum</i> : growth inhibition	[82]
Pepper	35 kHz, 21.4 W/L, 120 s, 65 °C	Improved firmness; color preserved	<i>L. innocua</i> : 7.4	[56]
	40 kHz, 120 s, +1% lactic acid	-	<i>E. coli</i> : 2.9, <i>S. enterica</i> Enteritidis: 2.8	[81]
	40 kHz, 400 W/L, SAEW+ mild heat	Color and firmness preserved	<i>L. monocytogenes</i> , <i>S. enterica</i> : 1.0–3.0	[21]
Plum	40 kHz, 100 W, 600 s, +40 mg/L ClO ₂	Reduced respiration rate; maintained acidity, flavonoid, and ascorbic acid	Aerobic mesophilic and aerobic psychotropic bacteria, yeast and mold: reduced counts	[8]
Sesame leaf	40 kHz, 400 W/L, 180 s, + SAEW + wash water	-	Yeast and mold: 1.76, <i>E. coli</i> : 2.33, <i>L. monocytogenes</i> : 2.4	[75]
Spinach	40 kHz, 400 W/L, 180 s, + SAEW + wash water	-	Yeast and mold: 1.97, <i>E. coli</i> : 2.41, <i>L. monocytogenes</i> : 2.49	[75]
	25 kHz, 79.41 W/L, 60 s	-	<i>E. coli</i> : 4.45, total aerobic count: 2.27, yeast and mold: 1.77	[63]
Strawberry	32 kHz, 10 W/L, 600 s + surfactant	-	<i>E. coli</i> : 1.96	[74]
	20 kHz, 30 W/L, 300 s, + O ₃ + ClO ₂	Maintained quality and physicochemical properties	<i>B. cinera</i> : growth and decay incidence inhibition	[10]
	35 kHz, 21.4 W/L, 120 s, 65 °C	Improved firmness; anthocyanin and color retained	Total mesophiles: 8.24	[56]
	40 kHz, 250–350 W, 600 s	Improved firmness, soluble solids, acidity, and vitamin C	Total bacteria: 1.9–2.42, yeast and mold: 1.35–2.45	[90]
	40 kHz, 24 W/L, 600 s + SAEW	Maintained physicochemical properties	Total aerobic bacteria, yeast and mold: 1.29	[83]
	37 kHz, 30 W/L, 3600 s, + BPW + 24 kJ/m ² , 1200 s	-	<i>E. coli</i> : 3.04, <i>S. aureus</i> : 2.42, <i>S. Enteritidis</i> : 5.52, <i>L. innocua</i> : 6.12, HAdV: 2.73–3.98	[19,43]
	33 kHz, 60 W	Maintained physicochemical and antioxidant properties	Total bacteria count: 2.0, yeast and mold: 1.22	[71]

Table 2. Cont.

Fruit/ Vegetable	Ultrasound Parameters	Main Findings		Sources
		Quality Attributes	Microbial Log Reduction and Disease Incidence	
Tomato	20 kHz, 131.25 W/L, + NNEW	-	<i>E. coli</i> , <i>S. Typhimurium</i> : no detection	[80]
	45 kHz, 1140 s	Enhanced phenols; delayed color development	Total microbial count, yeast and mold: reduced count	[91]
	40 kHz, 24 W/L, 600 s + SAEW	Soluble solids; acidity and vitamin C maintained	Total aerobic bacteria: 1.77, yeast and mold: 1.50	[83]
	45 kHz, 600 s + peracetic acid	-	<i>S. enterica</i> : 3.90, yeast and mold: 3.4, aerobic mesophile: 4.44	[84]
	37 kHz, 30 W/L, 600 s, + BPW + 24 kJ/m ² , 1200 s	-	HAdV: 1.20–2.61	[43]
Watercress	35 kHz, 21.4 W/L, 120 s, 65 °C	Improved firmness; pronounced color difference	Total coliforms: 8.24	[56]
Zucchini	20 kHz + 0.165–8.2 kJ/m ² + blanching (60–90 °C)	-	<i>Enterococcus faecalis</i> , <i>Deinococcus radiodurans</i> : 1–3	[26]

VI: vacuum impregnation, BPW: buffered peptone water, PAL: phenylalanine ammonia lyase, PA: peroxyacetic acid, SA: salicylic acid, POD: peroxidase, SAEW: slightly acidic electrolyzed water, NNEW: near neutral electrolyzed water, MAP: modified atmosphere packaging, HAdV: human adenovirus.

The systems for nano-ZnO coating application on kiwifruit after US treatment have also been evaluated [89]. Although individual US treatment of kiwifruit was somewhat effective, sequential application of US at 40 kHz, 350 W, and 1.2 g/L nano-ZnO coating was more effective in senescence delay, mass and firmness loss reduction, and storage life extension. The addition of mild heat to US treatment have also been explored, where a more pronounced effect of US (35 kHz, 120 W, and 21.4 W/L) was reported at 65 °C on red bell pepper, watercress, and strawberry, with improved quality retention and enhanced reductions of 7.43, 8.24, and 8.10 log CFU/g for *L. innocua*, total mesophiles, and total coliforms, respectively [56]. Similarly, the efficacy of US at 40 kHz, 400 W/L combined with SAEW was also enhanced at 40 and 60 °C, respectively, for fresh cut kale and bell pepper [21,86,87]. Browning and off-odor were under acceptable limits for fresh cut kale, while hardness and color parameters for control and treated samples were not significantly different for bell pepper. Enhanced bactericidal efficacy led to 3.32, 3.11, 3.00, 3.97, 3.66, 3.62, and 3.24 log CFU/g reductions in *E. coli*, *L. monocytogenes*, *S. Typhimurium*, total bacterial counts, *Enterobacteriaceae*, *Pseudomonas* spp., and yeast and mold counts, respectively.

4. Combination of UV-C Radiation and US Technology

Some studies have begun to examine the development of hurdle techniques involving UV-C radiation and US technology, either in sequential or simultaneous application. Sequential application involves treatment with one technology immediately followed by others and has shown improved microbial reductions and minimized quality changes in zucchini squash [26]. Alternative blanching treatments of UV-C radiation (1.17–8.2 kJ/m²) followed by thermosonication (20 kHz, 90 °C) induced 3 log reductions in *Enterococcus faecalis* and *Deinococcus radiodurans*, compared with 1 log reduction achieved from individual treatment with UV-C radiation. Birmpa et al. [19] demonstrated that sequential application of US at 30 W/L followed by UV-C radiation at 24 kJ/m² evoked better log reductions (2–3 log) of human adenovirus (hAdVs) with less processing time, compared with individual results of UV-C radiation (2.13, 0.92, 1.25 log) and US (0.85, 0.36, 0.53 log) on lettuce, cherry tomato, and strawberry, respectively.

Simultaneous application, on the other hand, applies both technologies at the same time with enhanced results in disinfection efficacy and functional properties. A constant US intensity of 13.87 W/L from a 40 kHz, 1 kW transducer and UV-C radiation dosage of 0.72–10.76 kJ/m² revealed increasing reduction in the population of total aerobic bacteria on tomato and up to 2.33 log reduction, while yeast and mold were undetected at higher dosage levels [22]. Enhanced biosynthesis and extractability of phytochemicals were also reported in tomato, with 36, 60, 30, and 90% increases in antioxidant activities, vitamin C, total phenols, and lycopene contents, respectively [1,92]. The combined effects of UV-C radiation and US cavitation were observed to disrupt the structural integrity of macromolecules and chemical bonds of tomato phytochemicals, which stimulated their accumulation and facilitated their extraction. Collectively, these few studies present the potential of a hurdle technology involving UV-C radiation and US technology for the postharvest decontamination of fruits and vegetables, with this area of focus warranting further exploration.

The theory elucidating the mechanism of the synergy between US technology and UV-C radiation can be explained from their individual mechanisms of operation. It is possible that the resultant mechanical effect of the collapse of transient cavitation from US technology, which includes high heating and cooling rate (10⁹ K/s), shock wave formation, high temperature (5000 K), and pressure (1000 atm), ruptures microbial cell envelopes [93]. The ruptured cell envelopes then facilitate access of UV-C radiation to light-sensitive DNA of the microorganisms within a short processing time. The formation of cyclobutane thymine dimers from the action of UV-C radiation combined with chemical effects of OH[•] and H⁺ species formation from US technology eventually offers a more potent bactericidal effect that is capable of depleting microbial growth, leading to the eventual death of microorganisms [42,93]. However, this theory needs to be properly tested from more studies and relevant tools.

5. Future Perspectives and Industrial Relevance

The low penetrating capacity of UV-C radiation into opaque substances, high energy consumption, and long treatment time associated with US technology has limited their individual usage. Thus, research in the applications of UV-C radiation and US technology for postharvest decontamination of fruits and vegetables is focused on hurdle technology of combination applications, which have shown enhanced decontamination efficiency. The hurdle technology has shown potential of overcoming limitations and harnessing advantages of each individual technology. As studies reported on this hurdle technology are relatively few, it is necessary to have more validation towards achieving industrial-scale applications. Scale-up studies to larger proportions would reveal important considerations to ensure uniformity of US cavitation and UV-C exposure on food surfaces due to variations in ultrasonic field and non-penetrative ability of UV-C radiation, which have been observed as the most important challenges to the commercialization of US technology and UV-C radiation for fresh produce decontamination [63,94]. The use of agitation in free-flowing US baths and application of mixed-mode US frequencies can reduce standing-wave effects and creation of different cavitation bubble size to ensure uniform cavitation [20,63]. Wide variations in UV-C radiation intensity can be reduced so that energy reaches the samples more effectively [26]. The radiochromic film dosimetry approach could also be introduced to UV-C treatment to measure or evaluate exposure of radiation dose. Film dosimetry is reportedly associated with measuring and verifying the dosage level on food substances during irradiation [94,95]. Once non-uniformity of irradiation or wide variations in dose is established, a system to rotate irradiated samples as described by Yan et al. [26] can be introduced to ensure UV-C dosage uniformity on the samples for improved efficiency, especially in high loading industrial applications. For combination approaches of US technology and UV-C radiation, we can incorporate sanitizer solutions as the washing medium in US baths lined with UV-C radiation lamps to enhance efficiency and reduce cross-contamination. The heat generated from simultaneous combination energies, which may cause dehydration and damage the appearance of fresh produce, may be overcome by incorporating a water circulatory system that simultaneously introduces and drains water in the tank to help control temperature rise and ensure minimal cross-contamination. Identification of important factors influencing the decontamination process can be enhanced through better understanding of microbes' behavior where more accurate inactivation of target microorganisms can assist optimization of the process parameters for cost-effective practical applications.

6. Conclusions

The research on the postharvest decontamination of fruits and vegetables is rapidly evolving due to increased safety awareness and consumer demands for minimally processed foods with fresh-like characteristics. UV-C radiation and US technology have presented encouraging results in postharvest decontamination of fresh produce with minimal effects on quality characteristics. However, long exposure time, high US energy consumption, and limited penetration capability of UV-C radiation have plagued research in these areas. The potential for synergistic or complementary effects for improved efficiency have also been established when UV-C radiation or US technology is applied in combination with other antimicrobial techniques. The hurdle technology involving UV-C radiation and US technology offer substitute benefits towards ensuring overall safety and wholesomeness of fruits and vegetables in comparison with individual applications or their combinations with conventional approaches. More studies are required on this hurdle technology, while scale-up and optimization of the process will provide opportunities for industry-led collaborations and chart the path towards effective commercialization.

Author Contributions: Conceptualization, O.J.E. and N.L.C.; investigation, O.J.E.; resources, O.J.E. and N.L.C.; data curation, O.J.E.; writing—original draft preparation, O.J.E.; writing—review and editing, N.L.C.; supervision, N.L.C., Y.A.Y., and R.S.; project administration, N.L.C.; funding acquisition, O.J.E. and N.L.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universiti Putra Malaysia, grant number GP-I/2014/9439000, and the first author was funded by Niger Delta Development Commission, Nigeria (NDDC/DEHSS/2014PGFS/AKS/014), for postgraduate study.

Acknowledgments: The authors are grateful to Daniel Onwude for providing some insights and discussion of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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