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Review on Household Decontamination Technologies for Fruits & Vegetables

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Abstract Fruits and Vegetables are a rich source of vitamins & minerals and protect us from micronutrient deficiencies as well as gastrointestinal imbalances. Increasing demand for fruits & vegetables in recent few years have also led to an exponential increase in the occurrence of foodborne illnesses. These foodborne illnesses have often been linked to the pathogens found in fruits & vegetables, residual pesticides as well as organic & inorganic deposits. Household decontamination methods & techniques form the last barrier to prevent the illness carriers in the entire supply chain from farm to fork. In this review, we have summarized various decontamination techniques employed at household level to ensure safe intake. The techniques range from potable water wash to chemical aids to heat treatments to modern methods employed to reduce microbial load, residual pesticide level and organic/inorganic non-natural contaminants. No single technique was able to cleanse the produce as well as preserve integrity & sensorial parameters. Hence, multiple hurdle concept for combination technologies is the preferred way for future decontamination strategies. There is a need for research in identifying complimenting technologies, which can be used in combination to reduce contaminants as well as preserve the organoleptic properties and shelf life of produce.

Keywords Household Decontamination, Washing, Vegetables & fruits Cleaning, Microbial Load Reduction, Pesticide Removal

1. Introduction

India is the second-largest producer of fruit and vegetables in the world, contributing a total of 265 million tonnes of the produce to the global production annually in 2015. [1] The Indian Fruit & Vegetable market was valued at ~5000 Bn INR (2015) and is growing at 12%. [2] The per capita daily consumption of fruits and vegetables in Indian population has also increased by 15% over last decade to 150 g/capita/day. [3]

Along with fruits & vegetables consumption, Food borne disease (FBD) cases in India are also on rise. As per the 2015 WHO study by the Foodborne Disease Epidemiology Group (FERG), FBD cases in India are expected to rise from 100 million illnesses in 2011 to 150-177 million by 2030. [4] The main causes of foodborne illness are bacteria (66%), chemicals (26%), virus (4%) and parasites (4%). [5] A review of recorded foodborne disease outbreaks in India from 1980 to 2016 shows Staphylococcus aureus, Vibrio sp, Salmonella sp, E. coli, Yersinia enteroclitica and Norwalk-like virus are some important microbial pathogens responsible for FBD cases. [6]

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Outbreaks of FBD in India typically have been associated with raw milk & milk products, contaminated meat & poultry products, cooked & uncooked vegetables. [6] There have been reported instances of outbreaks related to pathogens from contaminated vegetables and fruits. [7] For example, outbreaks of Salmonella that affected 33 people (Maharashtra, India 1995) was linked to the consumption of contaminated vegetables. Also, recently in 2002 a food-borne outbreak which affected 130 nurses from a Delhi hospital was associated with Norwalk-like virus from eating salad sandwiches. Thus, there is an emerging awareness that fruits and vegetables are sources of food borne diseases.

In the wake of increased FBDs and globalized food economy, the concept of Good Agricultural Practices (GAP) [8] has evolved connecting wide range of stakeholders including governments, food processing and retailing industries, farmers and consumers. However, the application of GAP is in a nascent stage in India and very few farmer catering to the Modern Trade retailers or international buyers, are practicing them. [9] While the application of GAPs during growing and harvesting may help to reduce the risk of contamination, there is still a gap in terms of post-harvest handling and distribution of fruits & vegetables. Figure 1 shows potential contamination touch points in fruits' & vegetables' supply chain.

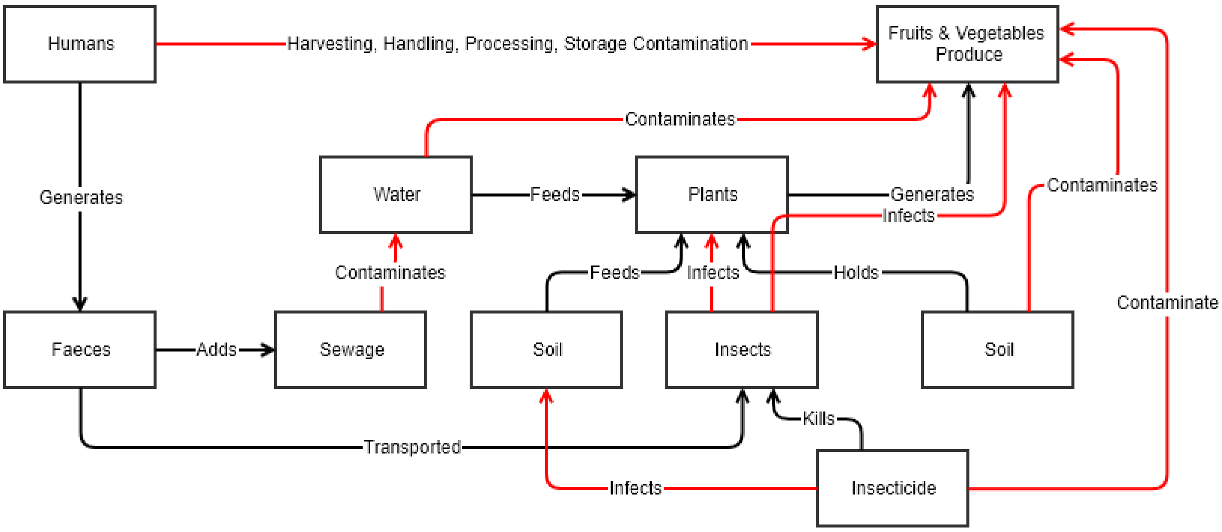

Figure 1. Fruits and Vegetables Contamination Touchpoints and Mechanism

Various produce disinfection techniques to control the FBD outbreak from fruits & vegetables are used at commercial scale, including chemical washing and spraying procedures, irradiative treatments, ultrasonication and natural/biological methods. The primary targets of such treatments have been the removal of pathogenic microbes and degradation of toxic chemical residues. Efficacy of the various cleansing methods in terms of scientific data to draw up conclusion is often debated. [10] Post cleansing at large commercial touchpoints, the vegetables and fruits bought from shops are usually washed with potable water in kitchen prior to consumption in order to remove any adherent soils and other non-natural residues clinging to their surface. However, potable water wash is found to be inadequate for removal of pathogenic microbes as well as the hydrophobic dirt housing non-natural things. [11] Other household processes such as boiling, peeling, blanching have also been studied to evaluate their antimicrobial and pesticide dissipation properties. However, these procedures have their share of disadvantages.

With the increasing fear of fruits & vegetables surface acting as carrier for communicable diseases and growing trends of micro-farming and globalized food chain [12], we would witness a resurgence in the end-consumer cleansing methods for eliminating pathogens from the surfaces of fruits and vegetables. Study of various factors linked to fruits and vegetables cleansing, for example - types of contamination agents, substrate surfaces classification, decontamination efficacy parameters, mechanism of decontamination systems, parameters of disinfection etc., is imperative to understand the objectivity of cleansing methods.

This paper investigates current literature regarding household decontamination techniques for fresh produce; specifically, the end-consumer decontamination strategies. It evaluates various household commodity decontamination techniques and their efficacy towards soil removal, pesticide dissipation, bacterial reduction, safety assessment, and sensorial deterioration. We also explored potential areas for further research relating to fresh produce decontamination at household level.

2. Methodology

A literature search was conducted using multiple databases such as Science Direct, Google Scholar, PubMed, PatSeer Patent Database etc. Initially, searches using keywords such as “fresh produce disinfection” and “fruits & vegetables decontamination” were undertaken. Searches also included relevant organizational and governmental websites related to food safety & disease control. After the initial exploration, the keywords were refined to search for comparison of various cleansing techniques and mechanistic pathways of decontamination. All papers were reviewed for content. Results from the papers are presented, discussed and conclusions drawn on implications for produce decontamination at consumer end.

Surface Contaminants on Fresh Produce

Fresh fruits have an external wax-coated protective covering, or skin that functions as a barrier for entry of most plant pathogenic microbes. The skin, however, harbours a variety of microbes including both bacteria and fungi as well as pesticides and grit. [9] Sources of contamination for fruits & vegetables can be classified into a) Pre-Harvest Contamination and b) Post-Harvest Contamination.

Contamination mainly occurs at the pre-harvest stage on fields due to run-off from nearby animal production farms, manure amended soil, contaminated irrigation water, and/or wild animal contact. [9] Fruits & vegetables skin get inoculated with a variety of Gram-Negative bacteria from sources such as the blowing air and carrier insects like the fruit fly. [8] Contact with soil, especially partially processed compost or manure, adds diverse human pathogenic microbes generally of the fecal-oral type as well as certain viruses. [10] Apart from microbial growth, the surface deposit of insecticides and pesticides are also found which are used during cultivation stage to prevent the crops from being damaged by pests, blights or other plant diseases. [13]

Source of contamination in post-harvest stage range from crops being handled by workers infected with transmissible diseases (*e.g.* Norovirus) to contaminated water being reused for washing the fresh produce. [14] Hand-picking the fresh produce inoculates the fruit surfaces with Staphylococcus. [15] Also, cross-contamination in the washing process in which pathogens from one lot of vegetables are transferred to another lot is considered as the source of the risk. [16] Due to improper storage and transportation of fresh produce fungal microflora growth occurs which includes molds and yeasts. [17] In some vegetables and fruits, a wax-like coating is externally applied to delay the loss of moisture for an extended life and to improve appearance. [18]

Broadly the surface contaminants in the two stages can be divided into four broad categories as mentioned in Figure 2 below.

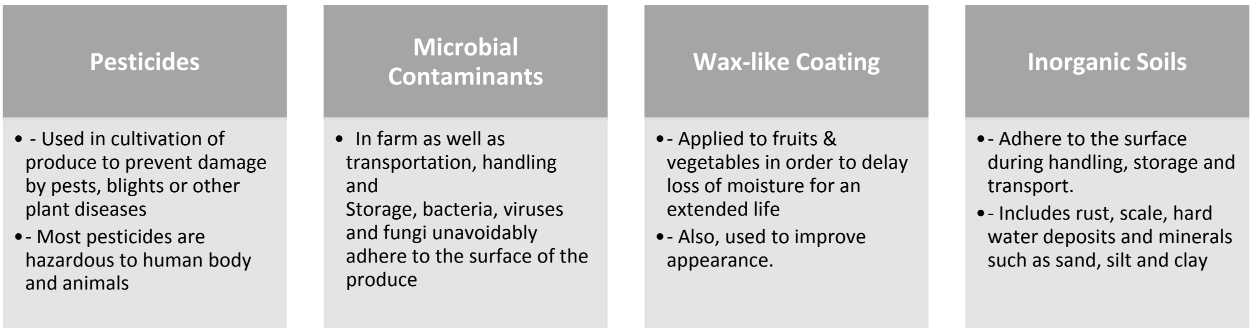

Figure 2. Surface Contaminants for Fresh Produce

Pesticides

The growing demand for fruits & vegetables produce has also led to an increased use of pesticides in farms and hence increased occurrence of these in soil, water, plants surface as well as produce surface. [19] Pesticides – strong chemicals – are designed to eliminate a variety of pests, weeds, bacteria and fungi. However, continued use of pesticides result in their accumulation on the surface of fruits & vegetables beyond the toxic level for human body. A maximum residue level (MRL) is the highest permitted level of a pesticide residue on fresh produce. [20] In India, a study conducted by Charan et al. in 2010 [21] revealed that 35.62% of total contaminated samples exceeded the MRL values. Exceeding the MRL values is a violation of GAP, and the consumption of such heavily contaminated produce may lead to serious health hazards.

Among various groups, organophosphates and carbamates are the most potent and widely used pesticides. [22,23] They are known to target the nervous system of pests resulting in the paralysis and eventual death of the organism. Besides their ability to kill insects, they have been reported to inactivate acetylcholinesterase in humans causing the accumulation of the acetylcholine, resulting in convulsions, seizures, and even death. [24] The carcinogenicity and genotoxicity of pesticides are thoroughly studied by various researchers. Table 1 lists the reported pesticides in fresh produces sampled from India.

Microbial Contaminants

Fruits and Vegetables have an external hydrophobic, wax-coated protective covering – skin – that functions as a barrier for entry of most plant pathogenic microbes. However, the skin itself harbours a variety of microbes and so the normal microflora of fresh produce is varied and includes bacteria, viruses and fungi. Table 2 mentions the list of common pathogenic microbes connected with fruits & vegetables.

Table 1. Pesticides identification in fresh produces reported in India

Pesticide	Produce Name	MRL	References
Monocrotophos	Brinjal, Cabbage, Tomato, Cucumber, Okra, Ridge gourd	0.2	[21, 25–27]
Chlorpyrifos	Okra, Cabbage, Cauliflower, Green Chilli, Mustard, Cucumber, Ridge gourd	0.2	
Cypermethrin	Brinjal, Okra, Tomato, Cucumber, Ridge gourd, Cucurbits	0.2	
Methylparathion	Brinjal, Cabbage, Cauliflower, Okra, Tomato	0.1	
Endosulfan	Brinjal, Cabbage, Cauliflower, Tomato, Cucumber, Okra, Ridge gourd, Crucifers	0.05	
Fenvalerate	Brinjal, Okra, Tomato	0.1	
Quinalphos	Brinjal, Cauliflower, Okra, Tomato, Mustard	0.1	
Dichlorvos	Potato	0.2	
Cyhalothrin	Tomato	1.0	
DDT	Okra, Pumpkin	0.05	

Table 2. Common Pathogenic Microbes identified in different fruits & vegetable produces

Type	Pathogen Name	Produce Name	Reference
Bacteria	Enterotoxigenic E. coli (ETEC)	Lettuce, Basil	[28]
Bacteria	Salmonella (non typhi) sps	Watermelon, Beans, Sprouts	[29]
Bacteria	Bacillus cereus	Sprouts	[30]
Bacteria	Enteropathogenic E. coli (EPEC)	Raddish, Sprouts	[31]
Bacteria	Shigella spp	Iceberg Lettuce, Salad	[32]
Bacteria	Staphylococcus aureus	Strawberries, Fruit Salad	[33]
Bacteria	Campylobacter spp	Cucumber, Lettuce	[34]
Bacteria	Clostridium botulinum	Vegetable Salad	[35]
Bacteria	Salmonella (typhi) sps	Root Vegetables	[36]
Bacteria	Escherichia coli spp	Raddish, Apple Cider, Lettuce	[37]
Virus	Hepatitis A virus	Iceberg Lettuce, Strawberries, Raspberries	[38]
Virus	Norovirus	Tossed Salad	[39]
Protozoa	Cryptosporidium spp	Apple Cider	[29]
Protozoa	Cyclospora cayetanensis	Raspberries	[40]
Protozoa	Giardia lamblia	Carrots	[41]

Table 3. Common Produces Artificially Waxed [42]

apples	avocados	bell peppers	cantaloupes	cucumbers	brinjals
mangoes	melons	nectarines	oranges	papayas	parsnips
pineapple	plums	pumpkins	rutabaga	squash	sweet potatoes
grapefruit	lemons	limes	passion fruit	peaches	pears

Table 4. Common contaminants in soil identified on produce surface [9,19,43]

Toxic metals (cadmium, copper, lead, mercury, tin)	**Fluoride**	**Sodium hydroxide**	**Zinc**	**Monosodium glutamate**	**Nitrites (food preservatives)**	**Iron**

Wax Like Coating

Some fruits and vegetables, especially those grown in warm climates, produce a natural waxy coating on the surface to prevent too much moisture from being lost. When the crops are harvested and produce is thoroughly cleaned before packaging and shipping, this natural wax gets removed. In case of no wax and long-distance transit, produce may arrive damaged. [42] So, produce handlers generally apply a thin coating of new wax. Both natural waxes (Carnauba, shellac, or resin) and petroleum-based waxes (usually proprietary formulae) are used, and often more than one wax is combined to create the desired properties for the fruit or vegetable being treated. [8] Waxes may be applied in a volatile petroleum-based solvent or via a water-based emulsion. Table 3 mentions the produces which are often waxed artificially.

Soil and Grit

Soil and grit can attach to vegetables during cultivation in open field, through wind, splashing from rain and irrigation, or mechanical harvesting, and can contaminate produce. Soil and Grit increases the hydrophobic properties of the produce surface and thus, hinders direct contact between the leaf surface and wash water, reducing decontamination efficacy. [43] Apart from pathogenic microbes, insecticides and pesticides, soil also harbours heavy metals and inorganic chemicals.

Household Decontamination Methods for Vegetables & Fruits

Various techniques are reported and currently followed to decontaminate fruits & vegetables from non-natural contaminants. The treatment is considered significant if a microbial reduction of 2 logs or more is obtained. [44] Similarly, any treatment lowering the residue levels of a pesticide below the regulatory MRL (FSSAI limit of 0.2 to 1.0) will be considered significant. [20] Also, the sensorial superiority of decontaminated produce – in terms of touch, smell or taste – explains the effectiveness of the removal of any wax or soil deposits from the produce surface. [45]

It is generally known and recognized among consumers that fruit and vegetables should be thoroughly washed before eating to remove dirt and other unwanted residues which can undesirably adhere to their surfaces. Some of the common techniques employed at home are listed in Figure 3.

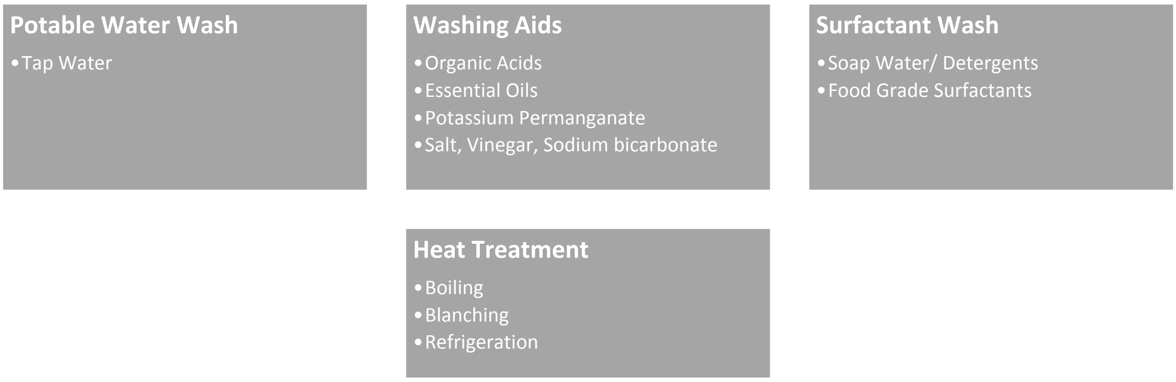

Figure 3. Decontamination Techniques broad classification

Table 5. Reduction of pesticide residues by plain water wash in some common produces

Pesticide	Vegetables	Exposure Time	% Reduction	Reference
Chlorpyrifos	Black Olive	1 min	26%	[46]
	Green Oilve	1 min	34%	[46]
	Bell Pepper	1 min	43%	[47]
	Tomato	2 min	35%	[48]
	Cauliflower	1 min	25%	[49]
	Potato	1 min	30%	[48]
	Spinach	1 min	33%	[48]
	Brinjal	1 min	34%	[48]
Cypermethrin	Black Olive	1 min	48%	[46]
	Green Oilve	1 min	48%	[46]
	Brinjal	2 min	35%	[50]
Deltamethrin	Tomato	2 min	10%	[51]
	Cauliflower	1 min	32%	[52]
	Potato	1 min	26%	[48]
	Spinach	1 min	10%	[48]
	Brinjal	1 min	26%	[50]
Lindane	Potatoes	Not Mentioned	21%	[53]
Hexachlorobenzene	Potatoes	Not Mentioned	24%	[53]
Diphenylamine	Apples	1 min	89%	[47]
Profenofos	Brinjal	1 min	99%	[54]
Methylparathion	Potatoes	Not Mentioned	18%	[53]
Imazalil	Lemons	1 min	42%	[47]
Cyhalothrin	Black Olive	1 min	26%	[46]
	Green Oilve	1 min	39%	[46]
DDT	Potatoes	Not Mentioned	18%	[53]

Potable Water Wash

Water is the basis for every possible cleaning agent, and it is also a solvent cleanser in itself. Tap water washing is the most commonly followed practice in every household before the processing of vegetables. However, water alone is not an effective cleaner because it has a high surface tension and does not wet surfaces effectively.

The effectiveness of plain water wash has been evaluated for insecticide and pesticide removal from vegetables in various reported studies (Table 5). The observations from reported studies is far from satisfactory.

The extent of residue reduction by washing depends on the physiochemical properties of the pesticides, such as water solubility, hydrolytic rate constant, volatility and octanol-water partition coefficient (K_{ow}), in conjunction with the actual physical location of the residues. Comparison of the data reported [20,51] on the residue cleansing of two pesticides (Deltamethrin = <0.2 µg/L, Chlopyriphos = 1.4 mg/L – solubility in water) on different vegetable surfaces by water wash is done in Figure 4.

Inadequacy of water in reducing the microbial load is also reported in scientific studies done on artificially contaminated fruits & vegetables.

- Water wash of cut lettuce, carrot and fennel in potable water for 5 min resulted in a decrease between 0.1 and 1 log of hepatitis A virus (HAV). [55]
- Also, Noro Virus (typically transferred to fruits/ vegetables from touch of workers infected with any transmissible diseases) on onion bulbs and spinach leaves was reduced by respectively 0.4 and 1.0 log after 5 min washing. [56]
- Nelson (2000) demonstrated that water washing of green peppers could reduce microbes by 0.5 to 1 log CFU/g depending on the extent of surface attachment. [57]

The reduction of microbial load reported is far from safe standards of 3-4 log reduction (99.9%- 99.99% reduction). It can also be stated that in naturally contaminated raw produce, microbial load complexed with soil particles or protein material could result in more difficult and variable decontamination efficiencies than on artificially contaminated produce, reported above.

Water's surface tension causes it to cling to itself and reject other, hydrophobic objects. The types of wax coating on fruits and vegetables as well as soil and grit are water-repellent and hence, they do not get washed off with potable water alone. Dakwa et al [43] used filter paper to quantify the amount of grit removed by tap water wash from leafy vegetables – spinach and lettuce. It was observed that only ~60-70% of the total removable grit was recovered using tap water. Thus, water has limited cleaning efficacy to remove wax or other organic substances from produce surface.

Washing Aids

Various household techniques used for fruits & vegetables cleansing entail increasing the potency of water by addition of ingredients which aid in better decontamination. Inadequacy of water alone as the decontamination agent was discussed in earlier section.

In general, the washing aids help destroy pathogenic microbes through one or more of the mechanisms mentioned in Figure 5. [58] Also, the degradation of pesticides is aided by these washing aids by promoting hydrolysis of pesticides to form water soluble compounds which are then washed away easily. [59] Apart from that, the ingredients also help loosen the dirt and solubilize or degrade the hydrophobic materials efficiently to ease their removal with wash water.

Organic Acids

Organic Acids like Lactic acid, acetic acid, citric acid, fumaric acid, etc are natural compounds that are generally recognized as safe. The bactericidal effect of weak organic acids is more significant than strong organic acids as they are more lipophilic and invade the cell membranes faster acidifying the interiors of the bacterial cells. [60] Organic acids are found in most of the naturally occurring foods. Studies reported with Organic Acids are listed in Table 6.

Organic acids present an easy, effective, and ready to use agents for home use decontamination. However, they do increase the respiration rate of the produce and the produce washed with Lactic Acid and Acetic Acid have shown initial signs of discoloration post treatment. [66,67] The organoleptic compromise and decreased shelf life represent a challenge and needs new strategies to ensure suitability of the produce in home use scenario.

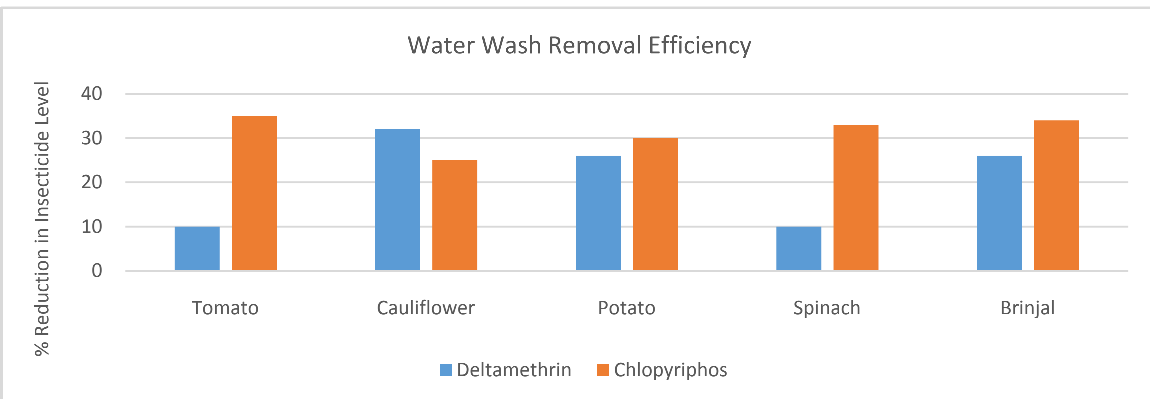

Figure 4. Removal Efficacy of Pesticides, with different water solubility, on vegetable substrates

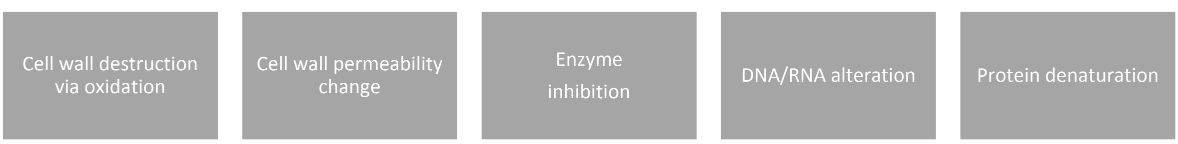

Figure 5. Mechanisms for Microbial Removal by chemicals in Washing Aids

Table 6. Organic Acids for reduction of Contaminants on fresh produce

Organic Acid	Substrate	Contaminant	Conc	Exposure Conditions	Reduction (log CFU/ %)	Reference
Lactic acid	Spinach leaves	E. coli Salmonella	2%	30 s | 55℃	2.7/g 2.3/g	[61]
	Tomato	E. coli	0.1%	2 min	2.2-2.5/g	[62]
	Iceberg	E. coli	0.5%	2 min	0.9/g	[60]
	Cabbage	L. monocytogenes	2%	5 min	3.41/cm^2	[63]
Citric acid	Apple	Total bacterial count	0.5%	5 min	1.5/g	[64]
	Cabbage	L. monocytogenes	2%	5 min	2.68/cm^2	[63]
	Lettuce	E. coli	1%	1 min	0.84/g	[60]
Malic acid	Cabbage	L. monocytogenes	2%	5 min	3.4/cm^2	[63]
	Lettuce	E. coli	1%	1 min	1.55/g	[65]
	Eggplant, okra, tomato, capsicum	Chlorpyriphos, Fenitrothion, Parathion	0.1%	10 min	40% to 82%	[59]
Acetic Acid	Lettuce	E. coli L. monocytogenes	1%	1 min	0.17/g 0.59/g	[60]
	Hot pepper Sweet pepper Eggplant	Profenofos	2%	1 min	61% 85% ~100%	[54]

Table 7. Essential Oils for reduction of Microbial load on fresh produce

Essential Oils	Substrate	Contaminant	Concentration	Exposure	Reduction (log CFU)	Reference
Oregano oil	Iceberg Lettuce	Salmonella	25–75 ppm	5 min	0.89-1.08 /g	[69]
	Eggplant salad	E. coli	0.7 – 2.1% v/w	5 min	2.5/g	[70]
Thyme oil	Iceberg Lettuce	Salmonella	0.02%	5 min	3.63/cm^2	[71]
	Lettuce Romaine	E. coli	0.10%	5 min	1.2/g	[72]
	Carrots	E. coli	0.10%	5 min	1.3/g	[72]
Basil methyl chavicol (BMC)	Iceberg Lettuce	Natural flora	0.1-1%	10 min	2.1/g	[73]
Carvacrol	Kiwifruit	Natural flora	150 ppm	10 min	3.3/g	[74]
	Honeydew melon	Natural flora	150 ppm	10 min	No reduction	[74]
Cinnamic Acid	Kiwifruit	Natural flora	150 ppm	10 min	3.0/g	[74]
	Honeydew melon	Natural flora	150 ppm	10 min	1.2/g	[74]

Essential Oils

Essential oils (EOs) are extracts from plant materials in the form of aromatic volatile liquids that are hydrophobic. Many studies have confirmed EOs to be antimicrobial agents against food spoilage pathogens. (Refer Table 7) Various mechanisms of action have been proposed to explain the extent of lethality of these compounds. The hydrophobicity of the EOs enable them to partition the lipids of the cell membrane and render the bacterial cell more permeable to the entry of these compounds as well as the leakage of cell contents. [68]

Though essential oils are effective and safe measure of microbial decontamination of fruits & vegetables; they often alter the sensorial properties of the original produce with their typical smell and taste – which also has a long residual effect. [75]

Potassium Permanganate

Potassium Permanganate is a powerful oxidant which is known to reduce the microbial count as well as degrade the pesticides. WHO guidelines suggest efficacy of topical application of $KMnO_4$ at very low concentration (1:10,000 dilution) on open wounds for germ killing, whereas the lethal effect being >10 gm. [76] So, washing fruits and vegetables with very low concentration (0.1%) KMnO4 solution followed by plain water wash is, thus, considered as a safe decontamination technique for fresh produce. Table 8 below captures the scientific studies reported on the decontamination of produce using Potassium Permanganate Solution in water followed by water rinse.

Acidified Sodium Chlorite

Acidified sodium chlorite (ASC) is a highly effective antimicrobial that is produced by lowering the pH (2.5–3.2) of a solution of sodium chlorite ($NaClO_2$) with any GRAS acid. [81] The FDA has recently approved ASC (0.5– 1.2 g/L) for spray or dip application on various food products, including fresh produce. [82] ASC is commercially supplied as a kit containing citric acid and $NaClO_2$. These chemicals when combined produce active chlorine dioxide (ClO_2), which is more soluble than sodium hypochlorite (NaOCl) in water and has about 2.5 times greater oxidizing capacity than hypochlorous acid (HOCl). [81] ClO_2 acts as the bactericidal agent by disrupting bacterial membranes and causing proton leakage, in turn compelling the cells to utilize more energy to maintain homeostasis. Reported literature in terms of antimicrobial effect of ASC on fresh produce is covered in Table 9.

A negative impact on the organoleptic properties of shredded carrots and strawberries have been reported while using ASC as the decontaminant. [84] Also, in acidic aqueous solutions the pesticides do not hydrolyse into their inactive forms and hence, little impact in pesticides degradation is expected using ASC. [86]

Other Wash Aids

Apart from the above ingredients, few other common household ingredients used by the consumers include salt (sodium chloride), vinegar (acetic acid), baking soda (sodium bicarbonate), lemon juice (citric acid), garlic juice and tamarind water (tartaric acid). Various reported studies for vegetables and fruits decontamination using the above washing aids is listed in table 10.

The efficacy was generally observed at higher concentrations of the common household ingredients and at that high concentration there is a sensorial after-effect to the produce cleansed.

Surfactant Wash

Surfactants are molecules that reduce the surface tension of water, helping it to spread out more uniformly. They also help penetrate, loosen and trap soil so you're really cleaning, not just moving dirt and grime from place to place. By adding tiny amounts of a compound known as a surfactant (Surface-Active-Agent), the active ingredients in all cleaners, the surface tension of the water is dramatically reduced from 73 dynes/cm to 30 dynes /cm, [43] allowing the water to spread over surfaces, penetrate dirt and lift it from surfaces. In common language - "surfactants make water wetter". Reduction in surface tension is captured in the Figure 6 for various commonly used surfactants including some of the Amino Acid based Surfactants.

Table 8. Potassium Permanganate decontamination efficacy as washing aid for vegetables

Substrate	Contaminant	$KMnO_4$ Concentration	$KMnO_4$ Exposure	Reduction (log CFU/ %)	Reference
Coriander leaves	Natural flora	0.10%	10 min	4.1/g	[77]
Leafy Chinese kale	Carbaryl Methomyl	0.001%	15 min	93.5% 47.6%	[78]
Tomato	Dimethoate Profenofos	0.01%	1 min	97.3% 88.1%	[79]
Cucumber	Dimethoate Profenofos	0.01%	1 min	90.2% ~100%	[79]
Cypermethrin	Okra	2%	30 min	56.90%	[80]
Hot pepper	Pirimiphos Profenofos	0.01%	1 min	66.5% 95.8%	[54]
Sweet pepper	Pirimiphos Profenofos	0.01%	1 min	93.3% 83.2%	[54]
Eggplant	Pirimiphos Profenofos	0.01%	1 min	96.8% 90.7%	[54]

Table 9. Scientific Studies on the Antibacterial efficacy of ASC on vegetable produce

Substrate	Contaminant	Concentration	Exposure	Reduction (log CFU)	Reference
Cilantro	Aerobic Mesophilic Bacteria E. coli Yeast and mold	1 g/L	30 min	3.5/g 3.5/g 4.0/g	[81]
Cilantro	Aerobic Mesophilic Bacteria E. coli Yeast and mold	0.1 g/L	30 min	1.4/g 1.3/g 1.6/g	[81]
Strawberries, carrots, tomato, lettuce, cucumbers, cantaloupes, apples	E. coli, L. monocytogenes, and Salmonella spp.	1.2 g/L	30 min	3/g	[83]
Carrots	E. coli	1 g/L	30 min	2.1/g	[84]
Chinese cabbage	E. coli	0.5 g/L	10 min	3.0/g	[85]

Table 10. Reported Studies on Vegetable Decontamination using common household ingredients

Wash Aid	Substrate	Contaminant	Concentration	Exposure Conditions	Reduction (log CFU/ %)	Reference
Sodium Chloride	Potatoes	Hexachlorobenzene Lindane DDT	10%	Not Mentioned	50.6% 47.2% 40.1%	[53]
	Cucumber	Chlorpyrifos Dimethoate Fenitrothion	5.0%	20 min	69.1% 65.2% 51.1%	[87]
	Cabbage	Chlorpyrifos DDT	10%	20 min	67.2% 65.0%	[88]
	Lettuce	Coliform Bacteria Other Bacteria Coliform Bacteria Other Bacteria	2% 10%	5 min	0.34/g 0.34/g 1.00/g 0.68/g	[89]
Sodium Bi-carbonate	Cucumber	Chlorpyrifos Dimethoate Fenitrothion Dichlorvos	5%	20 min	85.2% 76.1% 66.7% 98.8%	[87]
	Okra	Cypermethrin	5%	30 min	89.50%	[80]
	Brinjal	Chlorpyrifos Dimethoate Cyhalothrin	0.10%	10 min	21.5% 25.4% 30.4%	[90]
	Leafy Vegetable	Salmonella L. monocytogene	2.50%	15 min	1.5/g 1.8/g	[91]
Vinegar	Leafy Vegetable	Salmonella L. monocytogene	5.00%	3 min	1.5/g 1.3/g	[91]
	Carrot	Salmonella	4%	30 min	2.6/g	[92]
	Chinese Kale	Cypermethrin Profenofos	0.1%	10 min	50% 30%	[93]
	Cauliflower	Chlorpyrifos	10.0%	10 min	11.40%	[94]
Lemon Juice	Carrot	Salmonella	4.5%	30 min	2.7/g	[92]
Tamarind Water	Cauliflower	Chlorpyrifos	5.0%	10 min	93.00%	[94]
Garlic Juice	Cabbage	Cyhalothrin Dimethoate	5.0%	10 min	8.4% 11.5%	[95]

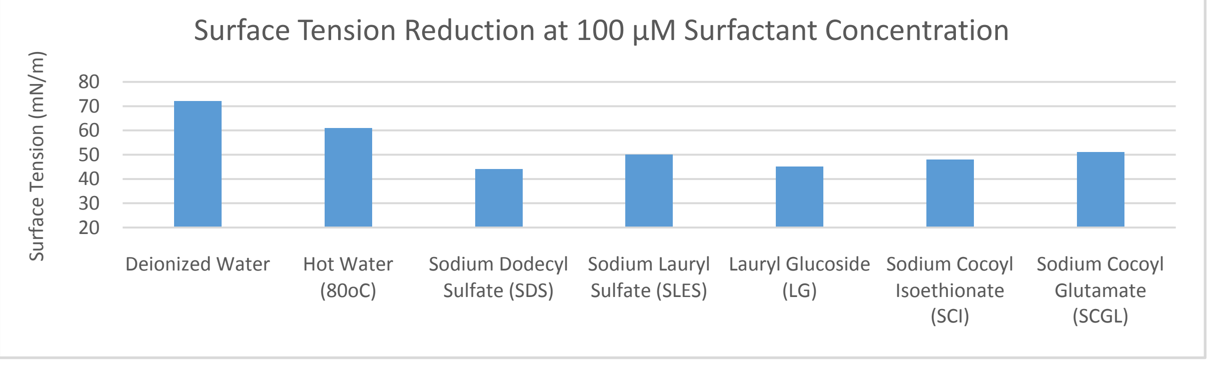

Figure 6. Reduction in the Surface Tension of Water with the help of common surfactants [96-98]

Surfactants Cleansing Mechanism

Surfactants present in the solution above their CMC have the ability to emulsify and solubilize the oily dirt which gets accumulated at the centre and hydrophilic materials at the surface of micelles. The attraction of the soil to the inside of the surfactant micelle helps loosen the soil from its surface. [96] Once the soil lifts off the surface, it becomes suspended in the water in the micelle. This suspension is also known as emulsification of one liquid into another. Happy inside the micelle, the soil will not settle back onto the surface. Now that the soil is trapped in the micelle and the micelle is suspended in water, it is easy to wash the soil way. The outside of the micelle is hydrophilic; so, as we rinse, the micelle floats away and we are left with a clean surface.

Figure 7 exhibits the mechanism of soil removal from substrate surface.

Surfactants Cleansing Efficacy

There are studies reported in literature exhibiting the efficiency of surfactants as better cleaning agent than water to remove surface residues from vegetables. One such study [43] describes the grit removal from the surface of baby spinach & lettuce comparing different washing solution treatments – tap water, peroxy acetic acid, and surfactant system – 0.05% Sodium Dodecyl Sulfate (SDS). (Refer Figure 8) SDS treatment aids in grit removal without affecting microbial quality, electrolyte leakage, colour parameters L∗, a∗, and b∗, shelf-life, and sensorial and organoleptic properties of baby spinach.

Microbial load reduction of various surfactants from various vegetable & fruits has been the subject of investigation of many studies – some of them are summarized in Table 11.

Quaternary ammonium compounds help reduce the microbial load effectively without adversely impacting the organoleptic properties as well as the structural integrity of produce. [103,106,107] Mode of action against bacterial cells involves a disordering of the lipid bilayer membranes by these surfactants. These compounds are reported to behave as bacteriostatic at low concentration and bactericidal at high concentrations. Bio-surfactants – like Alkylpolyglucosides and Acylglutamates – are found to exhibit low MIC values against a range of pathogenic microbes and being food grade surfactants would offer robust protection in produce cleansing. [107] Out of the numerous ionic (anionic or cationic) and non-ionic surfactants, majority of the reported studies are for sodium dodecyl sulfate (SDS) and polysorbates (such as Tween 20 and Tween 80) for the following reasons: (i) SDS is an anionic surfactant and an FDA-approved food additive (FDA 21 CFR 172.822), (ii) polysorbates are a class of nonionic surfactants and GRAS (generally recognized as safe) substances recognized by the FDA (21 CFR 172.840, 172.836, and 172.838).

Table 11. Studies on Microbial Load Reduction on Fresh Produce using Surfactant Solutions

Surfactant	Substrate	Microbial Pathogen(s)	Concentration	Exposure Conditions	Reduction (log CFU)	Reference
Benzalkonium chloride	Tomato	E. coli Y. enterocolitica	0.10%	1 min	2.5/g 4.2/g	[62]
	Lettuce	E. coli Y. enterocolitica	0.10%	1 min	0.4/g 1.6/g	[62]
	Lettuce	Mesophilic Bacteria	0.10%	15 min	2.3/g	[99]
	Lettuce	Mesophilic bacteria Lactic Acid Bacteria Total Coliforms	0.12%	5 min	2.1/g 2.9/g 2.8/g	[100]
Sodium Dodecyl Sulfate	Lettuce	E. coli Bacteriophage	0.10%	20 min	1.2/g 1/g	[101]
	Spinach	E. coli	0.10%	1 min	0.6/g	[102]
	Strawberry	Norovirus	0.02%	2 min	2.8/g	[103]
	Raspberry	Norovirus	0.02%	2 min	2.2/g	[103]
	Cabbage	Norovirus	0.02%	2 min	1.8/g	[103]
Lauric arginate	Lettuce	E. coli Bacteriophage	0.10%	20 min	2.1/g 2.0/g	[101]
Tween-20	Lettuce	E. coli Bacteriophage	0.10%	20 min	1.7/g 0.5/g	[101]
Tween-80	Spinach	E. coli	0.10%	1 min	0.5/g	[102]
	Strawberry	E. coli	0.02%	1 min	1.2/g	[104]
Cetyl pyridinium chloride	Brocolli	Salmonella L. monocytogenes E. coli	0.50%	1 min	2.5/g 4.1/g 1.9/g	[105]
	Cauliflower	Salmonella L. monocytogenes E. coli	0.50%	1 min	3.5/g 4.1/g 1.8/g	[105]
	Raddish	Salmonella L. monocytogenes E. coli	0.50%	1 min	3.1/g 2.5/g 1.0/g	[105]

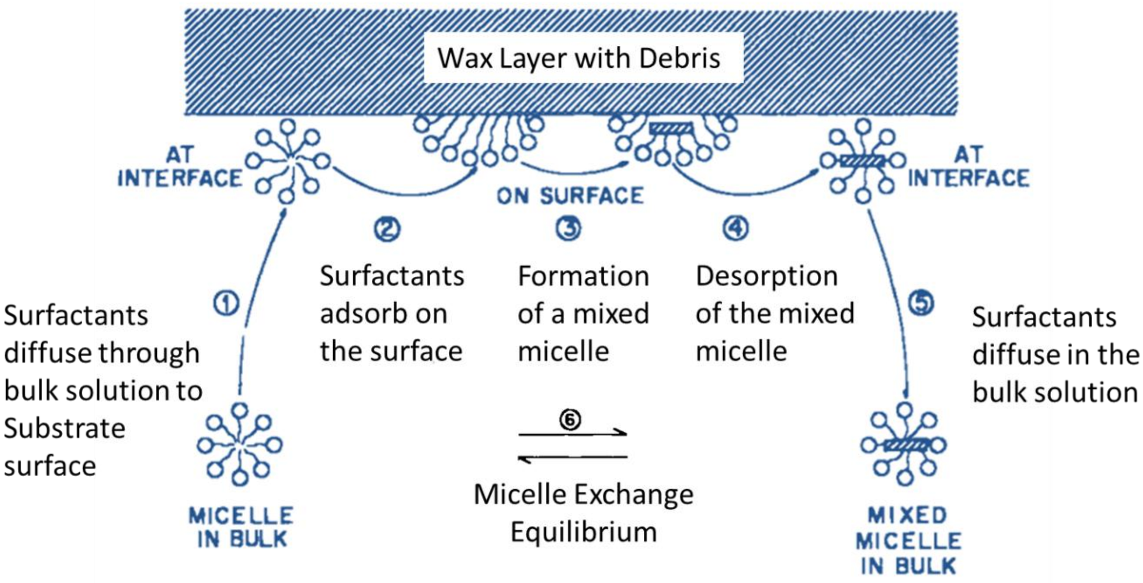

Figure 7. Schematic of Surfactant Cleansing Action in cleansing of hydrophobic residue from the surface of fruits & vegetables

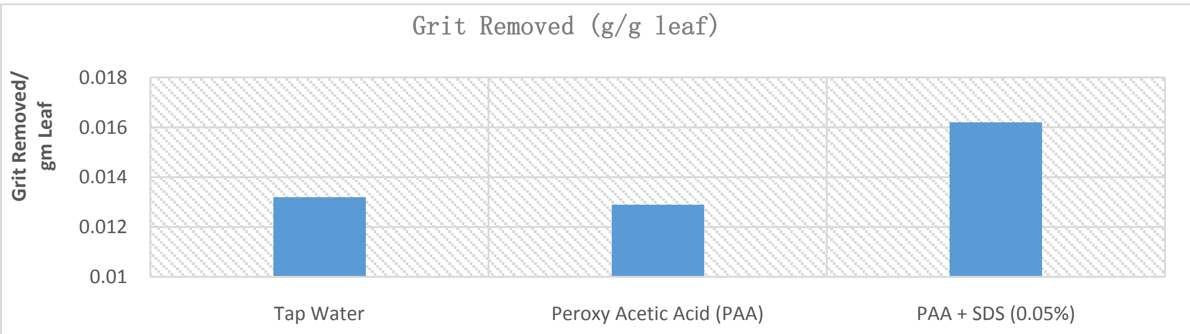

Figure 8. Grit removal efficiency improvement of water with addition of SDS – Adapted from the data by Dakwa et al [43]

Few studies reported in literature concerning the removal of pesticides by using surfactants are listed under Table 12.

Heat Treatment

Processes involving heat can enhance a) the inactivation of microbes and b) the volatilization and/or hydrolysis of the chemicals. [110] The thermal methods non-specifically kill cells by disrupting membranes, changing membrane permeability, or damaging proteins & nucleic acids by denaturation, degradation. [111] Some common thermal methods used in households include exposure to Boiling Water, hot water & cold-water treatment – blanching, freezing & refrigeration.

Blanching – Hot Water followed by Cold Running Water

Blanching is a process in which the vegetable or fruit is scalded in boiling/hot water, removed after a brief, timed interval and finally placed under cold running water. Bacteria are particularly sensitive to heat, and rapid kills – less than 1 minute per log (90%) reduction – are achieved at temperatures above 65℃. [112] Viruses are inactivated at temperatures between 60℃ and 65℃, but more slowly than bacteria. [112] Mild heating results in the inactivation of enzymes and hence, the reduction of microbial contamination. Depending upon the chemical properties of pesticides blanching helps to reduce the pesticide residue content. Literature studies describing the effect of hot water on produce cleansing is collated in Table 13.

Refrigeration and Freezing

Storing the fresh fruits and vegetables at cold temperature is one of the most common methods to preserve the decay. Refrigerators used in home kitchens maintain temperatures between 0°C and 7℃. Another way of reducing the temperature is soaking the produce in ice-cold water. Cooling of produce by storage in refrigerator minimises the effect of microbial activity, metabolic activity, respiration rate, and ethylene production, whilst reducing the ripening rate, water loss, and decay, thereby preserving quality and extending shelf life. [115] However, the pesticide degradation rate reduces at low temperature and hence, the chances of pesticide breakdown on cooling. [116] Studies related to produce decontamination using cold temperature are tabulated as Table 14.

Table 12. Pesticide Removal from Fruits & Vegetables using Surfactant Systems

Surfactant	Substrate	Pesticide(s)	Concentration	Exposure Conditions	Reduction (%)	Reference
Benzalkonium chloride	Tomato	Dichlorovos	3.00%	15 min	70.7	[108]
Sodium Dodecyl Sulfate	Peach	Chlorpyrifos Malathion Methylparathion	5.00%	3 min	32% 8% 10%	[109]
Rhamnolipid	Lettuce	Cypermethrin	0.02%	5 min	80%	[107]

Table 13. Decontamination of produce with High Temperature treatment

Substrate	Contaminant	Temperature	Exposure	Reduction (log CFU/%)	Reference
Potatoes	Hexachlorobenzene Lindane DDT Dimethoate	70℃	5 min	28.3% 22.9% 26.0% 47.3%	[53]
Sweet Pepper	Profenofos Methylpirimiphos	90℃	5 min	98.1% 99.1%	[54]
Eggplant	Profenofos Methylpirimiphos	90℃	5 min	99.9% 99.9%	[54]
Cucumbers	Enterobacteriaceae Total Aerobic Microbe	80℃	1 min	2.4/g 2.8/g	[113]
Sweet green peppers, onions, peas	Listeria monocytogenes	75℃	10 s	5.0/g	[114]

Table 14. Decontamination of produce with Refrigeration treatment

Substrate	Contaminant	Temperature	Exposure	Reduction (log CFU/%)	Reference
Cabbage	Chlorpyrifos DDT Cypermethrin	4 ℃	48 h	3.4% 2.6% 3.1%	[88]
Grapes	Methamidophos	4 ℃	48 h	0.6%	[116]
Cucumber	Diazinon Malathion	4 ℃	48 h	5.3% 14.7%	[117]
Tomato	Salmonella	7 ℃	48 h 10 days	1.5/g 3.0/g	[118]
Broccoli	L. Monocytogenes	4 ℃	48 h	1.1/g	[119]

Biological Techniques

Bio-preservation is a technique which employs competition between beneficial and pathogenic microrganisms to inhibit the growth of latter [120]. The fermentation products as well as beneficial bacteria like Lactic Acid Bacteria (LAB) are generally selected in this technique to control spoilage and render pathogen inactive. LAB produce antimicrobial compounds such as bacteriocin, organic acids and hydrogen peroxide [121]. The most common LAB bactriocin – an antimicrobial peptide – is Nisin which has been approved by Food and Drug Administration (FDA). Nisin acts on the cell membrane forming pores that result in cell death [122]. Another key classes of biological material which exhibits promising role in food preservation and safety are bacteriophages and lysins. Bacteriophages are viruses that infect bacteria causing their lysis and at the last stage of lytic cycle the hydrolytic enzymes are produced – called Lysins [123]. Various studies reporting the antimicrobial action from the biological entities on the fresh produce decontamination are captured in Table 15.

Degradation of pesticides by microorganisms is a commonly observed process in farms, soil, water, sewage, sludge etc. Findings have been reported on degradation of chlorpyriphos and methyl parathion (97% and 98% respectively) using a mix of bacteria (Acinetobacter sp, Pseudomonas sp, Proteus sp, Bacillus sp, and Flavobacterium sp) [124]. In the same study, it was observed that the metabolites formed post degradation (chlorpyriphos → 3,5,6-trichloro-2-pyridinol) inhibits the growth of microorganisms. However, no study has been reported on pesticide degradation from the surface of fresh produce using bacterial technique.

Modern Methods

At-Home modern techniques for fruits & vegetables cleansing are mostly safe & efficient scaled down versions of the established commercial methods. There is an increasing number of market launches of devices with in-situ, regulated exposure of chemical or physical agents to the fresh produce surfaces. Most promising of these modern methods includes Electrolyzed Water, Ozone Generators, Ultrasound and UV Irradiation Sanitizers.

Electrolyzed Water

Electrolyzed water (EW) has become increasingly popular over the last few decades as a unique broad-spectrum sanitizing option. EW can be produced using tap water with table salt as the chemical additive. Domestic use of EW is limited by its pH and ranges from neutral (pH=6.5 to 7.5) to slightly acidic EW (pH = 5 to 6.5) to slightly alkaline EW (pH = 8 to 10). [130] EW used for fruit and vegetable disinfection at home has recommended pH between 4.5 to 8.5 and Oxidation-Reduction Potential (ORP) between 500 – 700 mV. [131] Neutral EW (NEW) and Slightly Acidic EW (SAEW) is generated at home using an EW Generator which entails passing direct current in salt solutions of NaCl, KCl, or acids like HCl placed in an electrolytic cell with inert anode and cathode that are not separated by a dielectric membrane. The disinfection activity of EW is attributed to the presence of chlorine species, amount of free chlorine available, and the oxidation-reduction potential. Efficacy of produce decontamination using NEW and SAEW in literature studies is captured in Table 16. Specific research in the domestic use of EW for produce decontamination is needed to design a unit which is efficient, cost-effective and safe.

Table 15. Microbial Load Reduction of fresh produce using Biological Techniques

Substrate	Contaminant	Biological Agent	Exposure time	Reduction (log CFU)	Reference
Cantaloupe	L. monocytogenes	LinM‑AG8, LmoM‑AG13, and LmoM‑AG20	6h	3.5/g	[125]
Alfalfa Sprouts	E. Coli	EcoM‑HG2, EcoM‑HG7, and EcoM‑HG8	24h	2/g	[126]
Spinach	E. Coli Salmonella	8 log CFU/g of LAB culture	2h	1.9/g 1.6/g	[127]
Lettuce	S. Typhimurium S. Enteritidis	Lytic bacteriophages (UAB_Phi 20, UAB_Phi78, and UAB_Phi87	1h	3.9/g 2.2/g	[128]
Broccoli	L. monocytogenes	Nisin - 50ppm	1 min	4.35/g	[129]

Table 16. Decontamination of produce with Electrolyzed Water – Neutral and Slightly Acidic

Substrate	Contaminant	pH	Temperature	Exposure	Reduction (log CFU/%)	Reference
Apple	Cronobacter sakazakii	8.3	4℃	30 min	1.0/g	[132]
Melon	Cronobacter sakazakii	8.3	4℃	30 min	1.2/g	[132]
Pear	Cronobacter sakazakii	8.3	4℃	30 min	1.1/g	[132]
Lettuce	Aerobic mesophilic bacteria Enterobacteriaceae Pseudomonas spp.	7.5	4℃	5 min	1.86/g 1.91/g 1.0/g	[133]
Strawberry	Total Bacteria Yeast & Mould	6.2	23℃	3 min	0.93/g 0.96/g	[134]
Spinach	Omethoate DDVP Acephate	2.3	25℃	30 min	62% 59% 74%	[135]
Spinach	Omethoate DDVP Acephate	11.6	25℃	30 min	75% 46% 86%	[135]
Grapes	Acephate Cyprodinil	4.5	4℃	15 min	31.5% 43.8%	[136]

Ozone Generators

Ozone (O_3) is a potent oxidant molecule and has been used to kill microorganisms at industrial scale – mostly in waste water treatment and agricultural processing. The oxidizing potential of Ozone is 1.5 times more than chlorine [137] and it is effective over a wider spectrum of microorganisms – viruses, bacteria and fungi. [138] Ozone kills bacteria such as Escherichia coli, Listeria, and other food pathogens much faster than traditionally used disinfectants and is free of chemical residues. [139,140] The efficiency of ozone depends on its solubility in water, temperature, pH, and humidity. [141,142]

Ozone is considered hazardous and hence, various agencies have established recommendations on the human exposure to ozone. [142] For examples, 1) Food and Drug Administration (FDA) requires ozone output of indoor devices to be no more than 0.05 ppm; 2) Occupational Safety and Health Administration (OSHA) requires that workers not be exposed to an average concentration of more than 0.10 ppm for 8 hours; and 3) EPA's National Ambient Air Quality Standard for ozone is a maximum 8 hour average outdoor concentration of 0.08 ppm. However, in 2001, the U.S. FDA declared ozone as GRAS and allowed its use in food and food processing. [143]

The consumer-grade ozone generators are in domestic use for deodorizing garages, basements and automobiles, hotel rooms, reducing the odor of garbage bins, deodorizing clothing, and sanitizing water & food. [142] Various studies reported for fruit and vegetable disinfection are captured in Table 17. More research is needed in the design of safe, efficient & affordable ozone generators for the decontamination of vegetables and fruits in a kitchen setting.

Ultrasound

Ultrasound technique involves inactivation of microbes by the use of pressure waves with a frequency of 20 kHz or more. The antimicrobial effects of ultrasonication are attributed to intracellular acoustic cavitations increasing the permeability and thinning of cellular membranes [148], localized heating [149], and production of free radicals [150].

The ultrasound waves generate the cavitation bubbles. These bubbles pass through the liquid media and create a series of expansion-collapse cycles creating a negative pressure. The localized fields of neighboring bubbles interact which result in their instability and collapse. Shock waves generated by the collapsing bubbles is strong enough to shear and break the cell wall and membrane structures of pathogenic microbes [151-153]. The chemical effect of ultrasonication further bolsters the antimicrobial effect of the technique. Published research have demonstrated that ultrasound generates a temperature increase at a localized level [149] inside a collapsing bubble which generates primary hydroxyl radicals [154]. The hydroxyl radicals oxidizes the cell wall components and causes DNA damage [155,156].

Table 17. Decontamination of fresh produce with Ozonated Water

Substrate	Contaminant	Concentration (ppm)	Temperature (℃)	Exposure time (min)	Reduction (log CFU/%)	Reference
Tomato	Aerobic mesophiles Dichlorvos Mancozeb	0.06 ppm 6 ppm 1 ppm	20℃	10 min 15 min 20 min	2.2/g 91.9% 43%	[131] [108] [144]
Cucumber	Aerobic mesophiles	0.06 ppm	20℃	10 min	0.88/g	[131]
Carrot	Aerobic mesophiles	0.06 ppm	20℃	10 min	0.85/g	[131]
Capsicum	Aerobic mesophiles Coliforms Yeast & Moulds	5 ppm	20℃	30 min	3.27/g 3.66/g 2.02/g	[145]
Lettuce	Aerobic mesophiles Coliforms Yeast & Moulds	1 ppm	20℃	30 min	3.09/g 2.47/g 2.15/g	[145]
Spinach	E. coli O157:H7 Salmonella spp.	1 ppm	12℃	15 min	1.1/g 0.9/g	[61]
Strawberry	Yeast and mold Fenitrothion Alpha-cypermethrin Chlorpyrifos	2 ppm 500 ppm 1 ppm 1 ppm	20℃	3 min 10 min 5 min 5 min	2.3/g 62% 50% 55%	[146] [147] [110] [110]
Brocolli	Iprodione Alpha-cypermethrin Chlorpyrifos	1 ppm	20℃	5 min	49% 49% 55%	[110]

Table 18. Decontamination of fresh produce with Ultrasonication

Substrate	Contaminant	Treatment Parameters	Exposure time (min)	Reduction (log CFU/%)	Reference
Cherry tomato	Total bacteria Yeast and mold	40 kHz	10 min	0.71/g 0.62/g	[134]
Cabbage	L. monocytogenes	37 kHz | 1550 W	5 min	0.77/g	[161]
Lettuce	E. coli L. innocua S. aureus S. enteritidis	37 kHz | 30 W	30 min	2.3/g 1.88/g 1.71/g 5.72/g	[156]
Iceberg Lettuce	E. coli L. innocua P. fluorescens	42 kHz | 100 W	10 min	2.61/g 2.23/g 1.1/g	[136]
Strawberry	Total bacteria Yeast and mold Chlorpyrifos Alpha - cypermethrin	40 KHz	10 min	0.52/g 0.30/g 79.1% 91.2%	[134] [160]
Strawberry	E. coli L. innocua S. aureus S. enteritidis	37 kHz | 30 W	45 min	3.04/g 6.12/g 2.41/g 5.52/g	[156]
Tomatoes	DDVP	300 W	15 min	89%	[108]
Cucumber	Trichlorfon Dimethoate Dichlorvos Fenitrothion Chlorpyrifos	300 W	20 min	82.9% 52.2% 49.8% 84.4% 63.0%	[159]

Table 19. Decontamination of fresh produce with UV Light

Substrate	Contaminant	Treatment Parameters	Exposure time (min)	Reduction (log CFU/%)	Reference
Apple	E. Coli L. monocytogenes Total bacterial count	UV - C, 3.7 kJ/m3	5 min	2.9/g 1.7/g 2.1/g	[164, 165]
Cabbage	L. monocytogenes	UV - C- 390 mJ/cm2	5 min	3.9/cm2	[161]
Lettuce	E. coli L. innocua S. aureus S. enteritidis	UV-C	45 min	1.75/g 1.27/g 1.21/g 1.39/g	[156]
Melon	C. sakazakii	UV - C 2.5–7.5 kJ/m2	20 min	1.8–2.4/g	[166]
Pear	E. coli L. monocytogenes	UV - C, 0.92 kJ/m3	1 min	2.1/g 1.7/g	[165]
Strawberry	E. coli L. monocytogenes	UV - C, 7.17 kJ/m3	8 min	2.0/g 1.0/g	[165]

Most published studies (Table 18) indicates relatively low antimicrobial efficiency of ultrasound at nominal exposure times and only under higher power and more exposure time could it become an effective alternative to the decontamination process [157,158]. The tiny implosions during bubble collapse also help in the pesticides reduction [159,160] from the surface of vegetabless, and the reduction rate was found to be time and power dependent. However, the use of ultrasound for produce decontamination in household setting needs more research to be an effective alternative.

Ultraviolet Light

Ultraviolet (UV) light induces antimicrobial action through the generation of photoproducts which alters the DNA helix of the exposed microorganism. One of these photoproducts - Pyrimidine dimers (formed between neighboring molecules of pyrimidine) are responsible for impaired DNA transcription and translation [162]. This alteration of DNA is described as mutagenic and lethal to the microbial cells [156]. UV-C light (wavelength 254 nm) has been approved for use in food products and juices [163]. The UV light treatment entails exposing the commodity directly to the UV-light; however, some studies suggest that water-assisted UV treatment is more efficacious than dry UV treatments [164]. The use of UV light to remove pesticides from fresh fruits and vegetables surfaces is not yet reported and needs exploration. Studies reported in the literature are summarized in Table 19.

UV Light treatment scores over other conventional treatments by preserving the integrity & organoleptic properties of fresh produce while eliminating harmful pathogens. UV light treatment does not leave any residual effect and helps extend the shelf life of fresh produce. More research is ongoing in the developement of miniaturized, kitchen-friendly UV treatment devices which are simple, effective and affordable.

3. Discussion

Majority of produce decontamination work, reported in scientific literature, has been devoted to the large-scale post-harvest decontamination techniques and methodologies. Even after following the GAP methodology, the vegetables and fruits travelling from farm to fork typically have varying level of contaminants in the form of pesticides, pathogenic microbes, inorganic soil, heavy metals and wax-like organic materials. We observed less focus and low awareness for the household decontamination techniques for fresh produce and the same gets reflected in the quantum of scientific research done in this area.

Although washing with potable water helps to remove the contaminants to a certain extent, sanitizers have been applied to enhance the disinfection of the produce. Potable water wash studies reported <1 log reduction in the microbial count as well as 20-40% reduction in the residual pesticides – both of which are far from satisfactory. We observed variation in the decontamination efficacy quoted for different substrates (fruits & vegetables type) which can be attributed to different factors - antimicrobial susceptibility of microbial species, physicochemical properties of the pesticides, pH & temperature conditions composition of the fruits and vegetables, and their topographical features. Epidermis of fruits & vegetables is composed of a hydrophobic multilayer cuticle constituted of cutin, which makes their surfaces highly water repellent. [167] Studies suggest that the bacterial surface charges and the hydrophobic interactions between the waxy epidermis and the bacteria play a vital role in the attachment to the fruit or vegetable surfaces. [168] Similarly, the stability of each pesticide varies depending on pH and temperature conditions, location of the pesticide deposit, characteristics of the pesticide (solubility), and duration of pesticide treatment & produce growth stage at the time of treatment. [169]

Washing aids are used to increase the decontamination potency of water solvent. In terms of microbial removal from the produce surface, organic acids, few essential oils and acidified sodium chlorite solution were found to be significantly effective (log reduction of 2.5 to 3.5/g exhibited). Common household ingredients like salt, sodium bicarbonate, vinegar, garlic juice etc do not exhibit substantial decrease in microbial count (mostly between 0.5–1.5 log reduction) as compared to potable water. Potassium permanganate and acetic acid are found to show good decrease in pesticide degradation while either little to no literature was found for other washing aids.

One of the key disadvantages of using the washing aids for fruits & vegetables cleansing has been the deterioration in organoleptic parameters. [75] The primary reason for that being the secondary residual layer formed on fruits & vegetables with the washing aids which have strong sensorial attributes in terms of smell & taste. Some observations to that aspect are captured in Table 20.

Table 20. Organoleptic Changes with Washing Aids reported in literature

Wash Aid	Substrate	Sensory	Observation	Reference
Acetic Acid	Iceberg lettuce	Taste	5% acetic acid could reduce 3 log population of E. coli, however, may impart the sensory quality by causing an unacceptable sour flavour	[170]
Acetic Acid	Parsley	Smell Color	>6 log reduction in the population of Shigella sonnei with 5.0% acetic acid treatment, however, pointed out that high levels of acetic acid resulted in a noticeable discoloration and a strong vinegar odour	[171]
Lactic Acid	Peas	Smell	Concentration beyond 1% was known to generate strong smell	[67]
Lactic Acid	Leafy Vegetable	Color Visual Score	Post 5 days, a clear reduction in the visual quality was observed for rocket leaves washed with Lactic Acid - samples scoring under the limit of acceptability	[172]
Acidified Sodium Chlorite	Leafy Vegetable	Color Visual Score	40% reduction in visual score at the end of day 5 was observed with ASC solution	[172]
Thyme - Essential Oil	Lettuce	Taste Smell Visual	Lettuce washed with EOs were not suitable in terms of overall appreciation by Day 7. The off-odor and off-after taste perceived were significantly more intense on Day 1 compared to control. Day 7 samples were more intensely different in sensorial	[75]

Table 21. Combination Technologies reported for Produce Decontamination

Substrate	Contaminant	Combination Hurdle	Combination Hurdle Effect	Individual Hurdle Comparison (if any)	Reference
Lettuce	E. coli L. monocytogenes	Ozone + Citric acid	Treatment with 3 ppm ozone combined with 1% citric acid for 1 min immersing resulted in 2.31- and 1.84-log reductions of E. coli and L. monocytogenes, respectively	5 ppm ozone treatment for 5 min gave 1.09-log and 0.94-log reductions of E. coli and L. monocytogenes, respectively	[177]
Strawberries	E. coli	Water assisted UV Light + Surfactant (SDS)	UV-light in combination with SDS for 60 s was able to reduce the E. Coli population by 3.3 log	100 ppm SDS, tapwater, UV Light for 60 s reduced E. coli on raspberries by 1.6, 1.6 and 2.2 log respectively	[178]
Raspberries	E. coli	Water assisted UV Light + Surfactant (SDS)	UV-light in combination with SDS for 60 s was able to reduce the E. Coli population by 5.1 log	100 ppm SDS, tapwater, UV Light for 60 s reduced E. coli on raspberries by 2.5, 2.0 and 4.4 log respectively	[178]
Lettuce	S. enterica	Ultrasound + Essential Oils	5 min exposure to Ultrasound in water containing essential oils- Thyme Oil and Oregano Oil - shows 3.7 log/cm^2 and 2.9 log/cm^2 reduction, respectively	Water alone without and with ultrasound exhibited a reduction of <1log/cm^2 and ~2 log/cm^2, respectively	[179]
Cherry Tomato	Total bacteria	Ultrasound + Slightly Acidic EW (SAEW)	Combination treatment for 10 min led to a reduction of 1.77 log	Ultrasonic and SAEW treatments alone for 10 min led to 0.7 log and 1.45 log reduction respectively	[134]
Strawberry	Total bacteria	Ultrasound + Slightly Acidic EW (SAEW)	Combination treatment for 10 min led to a reduction of 1.3 log	Ultrasonic and SAEW treatments alone for 10 min led to 0.5 log and 1.1 log reduction respectively	[134]
Cabbage	Total bacteria	Ultrasound + Slightly Acidic EW (SAEW)	Combination treatment for 3 min led to a reduction of 2.5 log	Distilled Water and SAEW alone for 3 min led to a reduction of <0.5, 1.7 log respectively	[180]
Spinach	Total bacteria	Ultrasound + Slightly Acidic EW (SAEW)	Combination treatment for 3 min led to a reduction of 2 log	Distilled Water and SAEW alone for 3 min led to a reduction of <0.5, 1.1 log respectively	[180]
Lettuce	E. Coli	Ultrasound + Organic Acids (Malic, Lactic, Citric Acid)	Combination treatment of Ultrasound + Malic Acid, Lactic Acid, Citric Acid for 5 min led to a reduction of 2.44, 2.33 & 2.49 log/g respectively	Water, Malic Acid, Lactic Acid, Citric Acid (at 1% w/w), Ultrasound alone for 5 min led to a reduction of 0.43, 1.73, 1.39, 1.77, 0.9 log/g respectively	[181]
Lettuce	L. monocytogenes	Ultrasound + Organic Acids (Malic, Lactic, Citric Acid)	Combination treatment of Ultrasound + Malic Acid, Lactic Acid, Citric Acid for 5 min led to a reduction of 2.63, 2.47 & 1.99 log/g respectively	Water, Malic Acid, Lactic Acid, Citric Acid (at 1% w/w), Ultrasound alone for 5 min led to a reduction of 0.23, 1.61, 1.17, 1.35, 0.84 log/g respectively	[181]
Cabbage	Mesophilic aerobic bacteria	Ultrasound + Benzalkonium Chloride (BKC)	Combination Treatment of Ultrasound + BKC led to a reduction of 2.5 log/g	Potable Water, Ultrasound, BKC alone led to a reduction of 0.3, 0.6, 2.2 log/g respectively	[182]
Apples	Total bacteria	UV Light + Citric Acid	Combination Treatment led to a reduction of 2.6 log/g	UV-C and Citric Acid alone treatments led to a reduction of 1.5 and 2 log/g respectively	[183]

Another key disadvantage with the washing aids used is the risk of cross-contamination in the produce washed during the cleansing process. [173] Given the different degree of adherence of contaminants on to the different substrates, cross-contamination poses bigger difficulties in terms of contaminating a clean surface and removal of contaminants. For instance, it is easy to remove pathogens from tomato & brinjal while not so easy to cleanse a porous substrate like cauliflower. So, in case the bucket wash includes tomato, brinjal and cauliflower in the vegetable mix – there is a bigger risk of cross-contaminating the cauliflower surface and the removal from that is more challenging. Quite a few literature studies are available listing the decontamination challenges in commercial set-ups for produce wash and the stress is on maintaining the wash water quality and using solubilizers as anti-redeposition agents for organic soil containing pathogens.

Surfactants are known for reducing surface tension of water and solubilizing organic components and they are known antimicrobial agents as well. Access to surfactants in household setting is also common and considered safe. Efficacy of a wide range of surfactants to inactivate bacteria and viruses, alone and in combination with other washing aids, on fresh produces has been examined with varying results. Quaternary ammonium surfactants and non-ionic surfactants have shown to reduce microbial population from 2 to 4 log CFU/g. While, anionic surfactant like SDS has not been that effective when used alone. Xiao et al. [174] demonstrated the importance of using surfactants at concentrations exceeding the critical micelle concentration (CMC) in order to realise their benefits. At concentration exceeding the CMC, surfactant molecules start to assemble into clusters called micelles which have a hydrophobic core to capture the dislodged organic soils. Surfactant wash have also been studied for impact on the color parameters as well as sensorial effects – no or marginal difference has been observed. Thus, surfactants help overcome the challenges posed by other washing aids and could be a suitable mode for cleansing of produces both alone as well as in combination with other wash aids.

Temperature, as mentioned earlier, is an important factor in the growth of microorganisms controlling respiratory, metabolic and enzymatic activities and transpiration of produces. In thermal treatment methods, blanching help inhibit the microbial growth but at the same time hampers the permeability of the cell membrane, which in turn increases the rate of moisture removal. In case of refrigeration, the beneficial effects are seen over an extended storage period and that too for microbial growth. Thus, the refrigerator cooling of fresh produce should be used in addition to other decontamination techniques.

Several emerging technologies aimed at completely avoiding or reducing the use of chemicals have been studied and are described in this review: natural antimicrobials based on the use of biological compounds - bacteriocins, bacteriophages and lysins; the use of modern methods – Electrolyzed Water, Ozonated Water, Ultrasound, UV light, etc. Consumer grade form of these technologies for kitchen use offer suboptimal cleansing efficacy, impractical exposure duration or unfavorable cost proposition.

There is a concept of 'Hurdle Technology' used in food preservation techniques which is defined as utilization of multiple factors and/or treatments – either simultaneously or sequentially – affecting microbial growth [175]. The premise of this concept is that intelligent combination of 'hurdles' – the inhibition or inactivation methods – even at sub-optimal levels when used individually are more effective at eliminating the pathogens when used in a combination. Idea is to create multiple hurdles for the pathogens and the effect of combination is more than that of individual in decontamination as well as maintaining the integrity of fresh produce. One of the most common example of Combination Treatment is the regime of vegetable/fruits washing followed in a household – Dipping of vegetables/fruits in water which is heated and which contains Washing Aids followed by Hand/Brush Scrubbing and a potable water rinse. Each of the hurdle – Thermal, Chemical, Physical – contribute to the decontamination and the efficiency is higher than any of the hurdle individually [176]. The same can be extended to various modern techniques as well as physical methods which at lower, affordable levels might not eliminate the entire pathogens but in combination with regular treatments can be far more effective. Table 21 presents few combination approaches of the hurdle concept reported by reserachers towards design of strategies and standard procedures for produce decontamination.

In post-COVID scenario, the need for hygiene and safety would be heightened and so will be the demand to ensure protection of the food intake. The same is reflected in multiple product launches in household fruits & vegetables cleanser segment and rapidly increasing awareness in consumer's mind regarding the need for these products. From the product developer's side, there is a need to identify effective, safe and easy to use decontamination treatments with multi-mechanistic targets of microbes' removal, pesticide degradation, grit & other non-natural deposits reduction while at the same time preserving the integrity of produce both structurally and sensorially. In order to facilitate the selection research in terms of designing the standardized protocols, relevant to the consumer usage practices and realistic conditions, is the need of hour.

4. Conclusions

With the growing demand for fresh vegetables and fruits as well as the growing concern for food borne diseases there is an urgent need for efficient and reliable cleansing methods to assure safe intake. The demand in this post-COVID world have also spiralled for safe & efficient techniques & methods for household decontamination of fruits and vegetables. Researchers around the globe are actively investigating various technologies from household chemicals to thermal processes to surfactant solutions for their efficacy in removal of pesticide residues or foodborne pathogens or organic/inorganic soils. The literature review on household decontamination techniques summarized various techniques and washing aids like organic acids, essential oils, household chemicals, surfactants and thermal treatments. The household techniques in use is a trickle down version of the technologies in commercial decontamination with dialled down levels by keeping in mind the safety and cost parameters. As studied extensively for the commercial produce decontamination technologies, no one technique is known to take care of all the different decontaminants effectively. The concept of hurdle technology would find more resonance in designing startegies for household decontamination. There is a need to conduct extensive research for identification of complimenting technologies, which can be used in combination to reduce microbial and pesticide contaminants as well as preserve the organoleptic properties and shelf life of the produce. Use of combination technologies may overcome challenges of reduced efficacy of individual treatments; however, the effectiveness of possible combination processes in dissipating different pesticide groups and inactivating a broad spectrum of microorganisms while preserving the produce integrity remains nascent.

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