

Studies on Decontamination techniques for seasonal fruits and vegetables from main markets of Noida, Uttar Pradesh, India

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Abstract. The relevance of fresh fruits in supporting immune function has grown notably during and after the COVID-19 pandemic, largely due to their abundance of essential nutrients, including vitamins, minerals, dietary fiber, and beneficial plant compounds. However, because these foods are typically consumed raw or minimally processed, they are especially prone to microbial, chemical, and physical contamination, which presents considerable public health challenges. This study assesses the effectiveness of various household-level decontamination strategies—such as rinsing with water, the application of mild chemical agents (including vinegar, lemon juice, and sodium bicarbonate), and thermal techniques like blanching and refrigeration—in reducing microbial contamination on frequently consumed fruits and vegetables in Noida, Uttar Pradesh, India. The investigation focused on four types of produce: spinach, okra, grapes, and apples. Standard microbiological methods were used to evaluate microbial load reductions at multiple dilution levels. Blanching and sodium hydroxide treatments emerged as the most effective, achieving up to 90–95% reduction in microbial count. In contrast, basic tap water rinsing showed only limited efficacy. Treatments involving organic acids and natural substances such as tamarind and garlic delivered moderate yet notable reductions. The study highlights the importance of using appropriate and accessible decontamination methods to ensure food safety while preserving the nutritional and sensory properties of fresh produce. These findings offer valuable guidance for safer household practices and inform urban food safety strategies.

KEY WORDS: Microbial Load, Household Decontamination, Food Safety, Organic Acids, Thermal Treatment, Fresh Produce.

1. INTRODUCTION

Fruits and vegetables are fundamental to human nutrition, providing essential phytonutrients, vitamins (such as A, C, and K), and minerals that promote overall health and help prevent chronic diseases such as cardiovascular disorders, diabetes, and certain cancers [1, 2]. The World Health Organization (WHO) emphasizes a daily intake of 400 grams of fruits and vegetables to combat non-communicable diseases [3, 4]. In recent years, there has been a substantial increase in the global production and consumption of fresh produce. For instance, the production of fruits and vegetables in India has risen dramatically, with the country contributing approximately 265 million tonnes annually, second only to China [5].

Despite their recognized benefits, the consumption of fresh and minimally processed produce remains a pressing concern. The production, harvesting, and handling of fruits and vegetables expose them to microbial and chemical contaminants, posing significant food safety concerns. Pathogens such as

Salmonella spp., *Escherichia coli*, and *Listeria monocytogenes* are the most common microbes, have been implicated in outbreaks associated with fresh produce [6]. Moreover, chemical hazards such as pesticide residues and mycotoxins further exacerbate these risks, especially in minimally processed produce consumed raw or with minimal thermal processing [7]. Numerous studies have shown that contamination can originate at multiple stages, including pre-harvest (e.g., soil, irrigation water, manure) and post-harvest (e.g., handling, transportation, and storage) [8, 9].

Household decontamination practices are often the final barrier against foodborne illnesses. At the consumer level, traditional household practices, such as washing and peeling, are common but often insufficient in removing embedded pathogens and chemical residues [10,11]. The effectiveness and feasibility of modern home remedies like chemical soaking (vinegar, sodium bicarbonate), blanching, and natural antimicrobials (lemon, garlic, essential oils) vary greatly, but they are promising substitutes [9, 12].

In line with the hurdle technology approach, which uses multiple preservation methods to improve quality and safety, this study incorporates a variety of independent treatments that function through different mechanisms—thermal, chemical, and physical—to simulate real-world applications where consumers may combine methods (e.g., vinegar soaking followed by refrigeration or blanching). The rationale behind this approach is that no single technique is likely to eliminate all chemical and microbial contaminants, and that a more thorough and efficient approach to microbial decontamination may be achieved by combining many treatments. These combinations preserve the fresh produce's sensory qualities while improving microbiological safety, which has synergistic effects. In line with new best practices in home food hygiene and small-scale food safety initiatives, the study offers insights into the possible synergistic usage of each therapy by assessing its effectiveness separately. Although treatments were applied individually for controlled analysis, the study's design allows for comparative insights into their potential synergistic use to enhance microbial safety while preserving sensory quality. This aligns with emerging best practices in domestic food hygiene and small-scale food safety intervention [13, 14].

This research was conducted to comprehensively assess the efficacy of both traditional and advanced household decontamination methods applied to seasonal fruits and vegetables. The study uses colony-forming units per milliliter (CFU/ml) as a benchmark to quantify microbial reduction following various treatments. These include basic water rinsing, organic acid applications (such as vinegar), thermal methods like blanching, and chemical agents, including sodium hydroxide, potassium permanganate, and essential oils. Four widely consumed produce items, spinach, okra, grapes, and apples, were procured from different marketplaces in Greater Noida, Uttar Pradesh, to ensure variability in contamination levels. The research prioritizes the evaluation of each method's practicality, cost-effectiveness, and microbial control, intending to recommend feasible strategies that Indian households can adopt to improve the microbial safety of fresh produce.

2. METHODOLOGY

2.1 Sample Collection and Preparation:

Four commonly consumed produce items—apples, grapes, okra, and spinach—were selected based on their popularity and varying surface properties. Samples were collected from retail stores and street

vendors in Greater Noida, Uttar Pradesh, ensuring a mix of sources to capture a range of contamination levels. Fruits and vegetables were placed in sterilized polythene bags and transported to the laboratory under refrigerated conditions (4°C–5°C). All analyses and treatments were performed within 24 hours to minimize microbial changes during storage.

2.2 Decontamination Treatments:

To evaluate the efficacy of household decontamination methods, each produce type underwent the following treatments, categorized into three groups:

2.2.1. Water Washing Techniques: (Table 1)

Tap Water Wash: Produce was washed under running tap water for 5 minutes.

Potable Water Wash: Samples were soaked in potable drinking water and manually rubbed for 5 minutes.

Lukewarm Water Wash: Samples were immersed in water at 40°C and manually rubbed for 5 minutes [15].

2.2.2 Temperature Treatments: (Table 2)

Blanching: Samples were immersed in boiling water for 1–2 minutes, followed by rapid cooling under running water.

Refrigeration: Samples were stored at 4°C–5°C for 48 hours before washing with distilled water [9].

2.2.3 Household Chemical Treatments: (Table 3)

Vinegar Solution (2%): Prepared by mixing 10 mL of vinegar with 500 mL of distilled water; samples were soaked for 10 minutes.

Lemon Juice (4.5%): A solution was prepared using 4.5 mL of lemon juice in 500 mL of distilled water; soaking time was 30 minutes.

Garlic Solution (5%): Prepared by crushing 25 g of garlic and mixing it with 500 mL distilled water; soaking time was 10 minutes.

Tamarind Solution (5%): Prepared by mixing 25 g of tamarind pulp in 500 mL distilled water; samples were soaked for 10 minutes.

Sodium Bicarbonate (2.5%): Prepared by dissolving 2.5 g of sodium bicarbonate in 500 mL of distilled water; samples were soaked for 20 minutes.

Sodium Chloride (2%): A 2% NaCl solution was prepared by dissolving 10 g of NaCl in 500 mL of distilled water; samples were soaked for 10 minutes.

Sodium Hydroxide (5%): Prepared by dissolving 5 g of NaOH in 500 mL of distilled water; samples were soaked for 30 minutes.

These methods are adapted from traditional household practices and validated by recent literature for food hygiene enhancement [16, 17].

2.2.4 Chemical Treatment: (Table 4)

Organic Acids: Acetic, citric, malic, and lactic acids were tested at varying concentrations (0.1%–1%) by adding drops to 500 mL of distilled water.

Potassium Permanganate (0.01%–2%): Samples were soaked in a potassium permanganate solution for 2 minutes.

Acidified Sodium Chlorite (ASC): Prepared by combining citric acid and sodium chlorite to generate active chlorine dioxide; soaking time was 20–30 minutes.

These methods target pathogen reduction while preserving nutrient profiles [18].

2.2.5 Essential Oils: (Table 4)

Thyme and Oregano Oils (0.15%–2.1 %): Samples were soaked in solutions with varying concentrations of essential oils for 5–10 minutes. Essential oils have shown significant antimicrobial activity in producing sanitation [9].

2.2.6 Hurdle Technology: (Table 5)

To accurately reflect real-world domestic food safety strategies, select produce underwent combinatory (hurdle) treatments that integrated physical, chemical, and thermal interventions. Hurdle technology is predicated on the principle that applying multiple sub-lethal stresses, when utilized synergistically, results in enhanced microbial reduction, often yielding superior outcomes compared to individual interventions [13].

Vinegar (2%) + Refrigeration: Spinach was immersed in a 2% vinegar solution for 10 minutes, subsequently undergoing refrigeration at 4°C for 48 hours.

Sodium Bicarbonate (2.5%) + Blanching: Okra was subjected to a sodium bicarbonate solution for 20 minutes, immediately followed by blanching in boiling water for 1 to 2 minutes.

Lemon Juice (4.5%) + Refrigeration: Okra was immersed in diluted lemon juice for 30 minutes, then stored at 4°C for 48 hours.

Sodium Bicarbonate (2.5%) + Refrigeration: Grapes were treated with bicarbonate, followed by refrigeration.

Sodium Chloride (2%) + Lukewarm Water (40°C) + Refrigeration: Grapes underwent sequential decontamination—NaCl soak, thermal loosening of debris, and cold storage.

Sodium Bicarbonate (2.5%) + Refrigeration: Apples were treated similarly to grapes for comparison.

The objective of this multibarrier strategy was to replicate realistic food handling practices and evaluate whether sequential, mild interventions could attain reductions comparable to severe single-agent treatments, all while preserving the quality of the produce [20, 9]. The summary overview of all the decontamination techniques used in this investigation, including both single and combination approaches, is mentioned in Figure 1.

2.2.7 Control samples: (Table 6)

Untreated produce samples were immersed in 100 mL of sterile saline and manually agitated for 2 minutes to extract the native surface microflora. The rinse was then serially diluted and plated for microbial enumeration. No decontamination procedure was applied to the control samples. For each fruit and vegetable, one sample group was retained without any decontamination treatment to serve as a control. These untreated samples were used to establish a baseline microbial load and enable a comparative evaluation of all washing techniques.

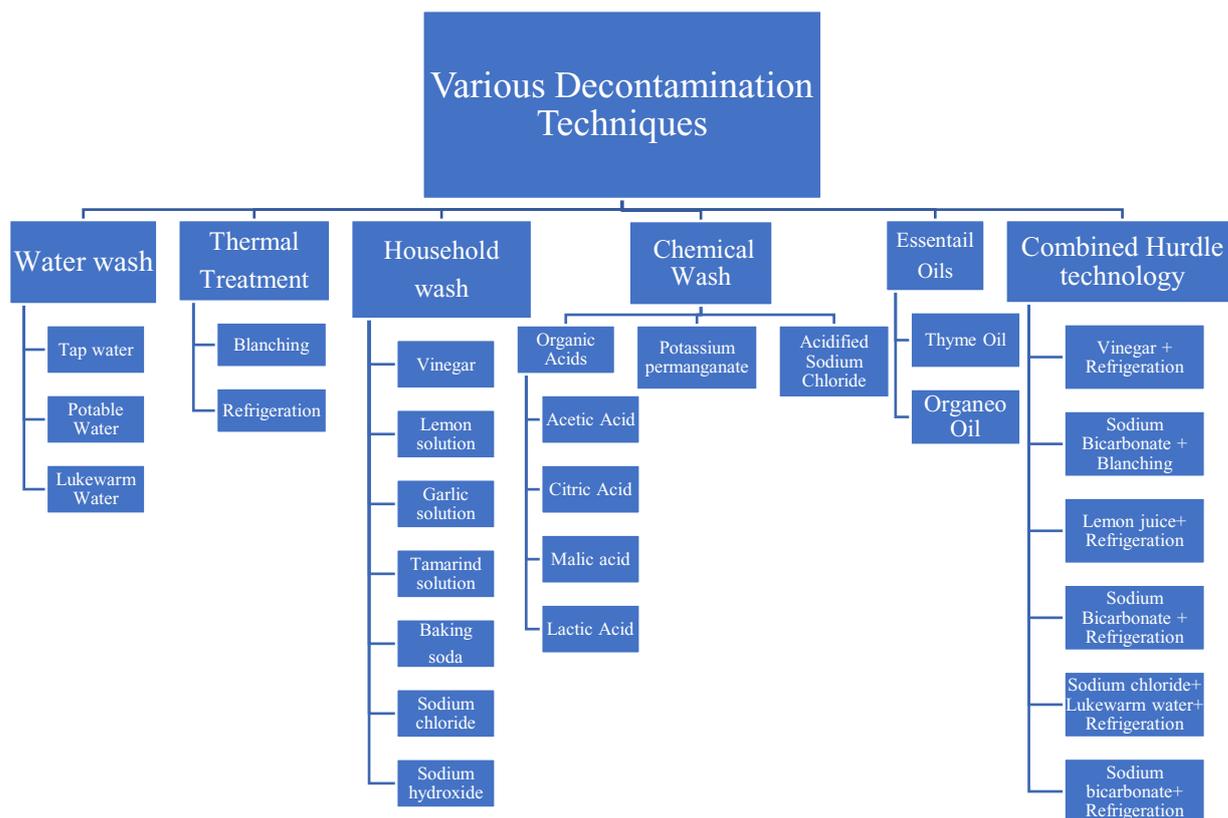


Figure 1: Categorization of Different Decontamination Methods Used in the Current Study on Fresh Produce; Diagram summarize the types of thermal, chemical, domestic, and essential oil-based treatments utilized for microbial decontamination are summarized in the figure. To maximize microbial reduction, combined hurdle technologies are a synergistic use of many techniques.

2.3 Microbial Analysis:

After each treatment, rinse water from the produce was collected and analyzed for microbial contamination. Serial dilutions (10-fold) of the rinse water were prepared using sterile saline (0.85% NaCl). Aliquots from appropriate dilutions (10⁻¹ to 10⁻⁶) were spread onto nutrient agar plates (for bacteria) and potato dextrose agar plates (for fungi). Plates were incubated at 37°C for 24–48 hours (bacteria) or at 28°C for 48–72 hours (fungi). Colony-forming units (CFUs) were counted on plates with 30–300 colonies to ensure statistical accuracy. Control samples underwent the same plating and dilution procedures without prior washing or treatment. The resulting colony counts were used to calculate % reduction for all decontamination methods. Each treatment was conducted in triplicate for statistical accuracy. Treatment concentrations were selected based on prior literature [15, 9] and optimized for household feasibility. All hazardous chemicals were handled in fume hoods with PPE.

2.4 Identification of Microorganisms:

After serial dilution, representative bacterial colonies from nutrient agar plates were stained with Gram stain to examine the shape and properties of their cell walls. Similarly, Lactophenol Cotton Blue was used to reveal hyphal structures in fungal colonies cultured on potato dextrose agar. The goal of these identifications was to categorize microbiological pollutants at the most fundamental morphological level. No additional molecular or biochemical testing was done.

2.5 Statistical Analysis:

Mean values and standard deviations were calculated for each treatment. One-way ANOVA (p < 0.05) was used to assess statistical differences between treatments.

Microbial reduction % was calculated as:
 (%) = (1 - Mean CFU of control / Mean CFU after treatment) × 100

3. RESULT AND DISCUSSION:

3.1 Evaluation of Microbial Load Reduction on Fresh Produce:

This section shows the observations made from the several decontamination procedures used on the four chosen produce items—apples, spinach, okra,

and grapes. Following each treatment, the microbial burden was measured using the conventional plate count and serial dilution techniques. The findings are tabular and include information on the percentage decrease from control samples, standard deviation, ANOVA values, and mean colony-forming units per milliliter (CFU/ml).

Table 1: Effect of Water-Washing Methods on Microbial Load Reduction in Fresh Produce

Produce	Treatment	Dilutions			Mean +/- S.D (CFU/ml)	ANOVA value	Reduction%
		10 ³	10 ⁵	10 ⁸			
Spinach	Tap water	1.6×10 ⁴	1.1×10 ⁶	9×10 ⁸	3 ± 5.20 ×10 ⁸	F= 5.53, P=0.0786	35.71%
Okra	Tap water	1.9×10 ⁴	1.5×10 ⁶	8×10 ⁸	2.67 ± 4.62×10 ⁸	F=4.33, P=0.1058	20%
Grapes	Tap water	2.1×10 ⁴	1.3×10 ⁶	9×10 ⁸	3± 5.20×10 ⁸	F=4.49, P=1.1016	30.77%
Apples	Tap water	1.8×10 ⁴	1.2×10 ⁶	8×10 ⁸	2.67 ± 4.62×10 ⁸	F=4.64, P=0.09975	27.27%
Spinach	Potable Water	1.4×10 ⁴	9×10 ⁶	7×10 ⁸	2.33 ± 4.04×10 ⁸	F=5.65, P=0.0762	50.10%
Okra	Potable water	1.2×10 ⁴	1.0×10 ⁵	6×10 ⁸	2.00± 3.46×10 ⁸	F=5.67, P=0.0758	40.07%
Grapes	Potable water	1.8×10 ⁴	1.2×10 ⁶	8×10 ⁸	2.67± 4.62×10 ⁸	F=4.49, P=0.1016	38.46%
Apple	Potable water	1.1×10 ⁴	7×10 ⁶	3×10 ⁸	1± 1.73×10 ⁸	F=13.85, P=0.0203	72.73%
Spinach	Lukewarm water	8.5×10 ³	8.8×10 ⁵	8×10 ⁸	2.67± 4.62×10 ⁸	F=5.53, P=0.0786	42.86%
Okra	Lukewarm water	1.1×10 ⁴	9.5×10 ⁵	7×10 ⁸	2.33 ± 4.04×10 ⁸	F=4.61, P=0.0983	30%
Grapes	Lukewarm water	9.5×10 ³	1.0×10 ⁶	7.8×10 ⁸	2.60± 4.50×10 ⁸	F=4.60, P=0.0985	40.00%
apples	Lukewarm water	8.9×10 ³	7×10 ⁵	4×10 ⁸	1.33± 2.31×10 ⁸	F=10.73, P=0.0306	63.64%

Values represent colony-forming units at three serial dilutions (10³, 10⁵, 10⁸), along with mean ± standard deviation of total microbial load. One-way ANOVA was performed to assess statistical differences between treatments (*P* < 0.05 considered significant).

Table 2: Effectiveness of Thermal-Based Decontamination Treatments

Produce	Treatment	Dilutions			Mean ± S.D (CFU/ml)	ANOVA value (F- statistic, p-value)	Reduction%
		10 ³	10 ⁵	10 ⁸			
Spinach	Blanching	4×10 ³	3×10 ⁵	2×10 ⁸	0067± 0.114×10 ⁸	F = 9.38, P=0.0376	85.7%
Okra	Blanching	5×10 ³	4×10 ⁵	3×10 ⁸	0.101 ± 0.1732×10 ⁸	F = 6.52, P=0.0628	70.1%
Spinach	Refrigeration	10×10 ³	8×10 ⁵	5×10 ⁸	0.169 ± 0.2892×10 ⁸	F = 5.61, P=0.0772	64.1%
Okra	Refrigeration	8×10 ³	6×10 ⁵	4×10 ⁸	0.135 ± 0.2309×10 ⁸	F = 5.27, P=0.0834	60%
Grapes	Refrigeration	10×10 ³	7×10 ⁵	3×10 ⁸	0.102 ± 0.1732×10 ⁸	F = 7.83, P=0.0487	76.7%

Apples	Refrigeration	7×10^3	4×10^5	2×10^8	$0.068 \pm 0.1155 \times 10^8$	F = 8.95, P=0.0401	81.7%
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Values represent colony-forming units at three serial dilutions (10^3 , 10^5 , 10^8), along with mean \pm standard deviation of total microbial load. One-way ANOVA was performed to assess statistical differences between treatments ($P < 0.05$ considered significant).

Table 3: Impact of Various Household Washing Agents on Microbial Load.

Produce	Treatment	Dilutions			Mean +/- S.D (CFU/ml)	Standard deviation	Reduction%
		10^3	10^5	10^8			
Spinach	Vinegar	9×10^3	1.3×10^5	1.3×10^8	1.29×10^8	F = 9.34, P=0.0378	85.8%
Okra	Vinegar	8×10^3	0.9×10^5	0.9×10^8	8.64×10^8	F = 13.41, P=0.0215	90.1%
Grapes	Vinegar	1.0×10^4	1.4×10^5	1.3×10^8	1.31×10^8	F = 10.05, P=0.0337	84.8%
Apples	Vinegar	7×10^3	0.8×10^5	0.8×10^8	7.70×10^7	F = 12.81, P=0.0231	91.0%
Spinach	Lemon solution	9×10^3	1.2×10^5	4×10^8	$0.0670 \pm 0.1155 \times 10^8$	F = 9.39, P=0.0376	85.8%
Okra	Lemon solution	7×10^3	0.8×10^5	2×10^8	$0.068 \pm 0.1155 \times 10^8$	F = 7.82, P=0.0488	80.3%
Grapes	Lemon solution	9×10^3	1.2×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F = 12.27, P=0.0248	92.4%
Apple	Lemon solution	6×10^3	0.7×10^5	2×10^8	$0.0670 \pm 0.1154 \times 10^8$	F = 8.42, P=0.0437	81.9%
Spinach	Garlic Solution	7×10^3	4×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F = 12.39, P=0.0244	92.9%
Okra	Garlic solution	6×10^3	4×10^5	2×10^8	$0.0670 \pm 0.1154 \times 10^8$	F = 7.69, P=0.0501	80.2%
Spinach	Tamarind solution	8×10^3	6×10^5	3×10^8	$0.0670 \pm 0.1155 \times 10^8$	F = 9.33, P=0.0379	85.8%
Okra	Tamarind solution	7×10^3	5×10^5	3×10^8	$0.0334 \pm 0.0577 \times 10^8$	F = 13.39, P=0.0215	90.1%
Spinach	Baking soda	6×10^3	3×10^5	2×10^8	$0.0670 \pm 0.1155 \times 10^8$	F = 9.32 P=0.0380	85.8%
Okra	Baking soda	9×10^3	6×10^5	3×10^8	$0.0002 \pm 0.0003 \times 10^8$	F = 17.99, P=0.0129	99.9%
Grapes	Baking soda	5×10^3	4×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F = 12.27, P=0.0248	2.4%
Apples	Baking soda	7×10^3	4×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F = 12.81, P=0.0231	91%
Spinach	Sodium chloride	8×10^3	5×10^5	3×10^8	$0.0670 \pm 0.1155 \times 10^8$	F = 9.32, P=0.0380	85.8%
Okra	Sodium chloride	7×10^3	5×10^5	3×10^8	$0.0334 \pm 0.0577 \times 10^8$	F = 13.39, P=0.0215	90.1%
Grapes	Sodium chloride	6×10^3	4×10^5	3×10^8	$0.1002 \pm 0.1732 \times 10^8$	F = 7.00, P=0.0574	77.2%

Apples	Sodium chloride	7×10^3	5×10^5	2×10^8	$0.0670 \pm 0.1155 \times 10^8$	F = 8.42, P=0.0437	81.9%
Spinach	Sodium hydroxide	6×10^3	4×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F = 12.39 P=0.0244	92.9%
Okra	Sodium hydroxide	4×10^3	3×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F = 13.39, P=0.0215	90.1%
Grapes	Sodium hydroxide	4×10^3	3×10^5	3×10^8	$0.0334 \pm 0.0577 \times 10^8$	F = 12.27, P=0.0248	92.4%
Apples	Sodium hydroxide	4×10^3	4×10^5	2×10^8	$0.0001 \pm 0.0001 \times 10^8$	F = 17.83, P=0.0132	100%

Values represent colony-forming units at three serial dilutions (10^3 , 10^5 , 10^8), along with mean \pm standard deviation of total microbial load. One-way ANOVA was performed to assess statistical differences between treatments ($P < 0.05$ considered significant).

Table 4: Microbial Load Reduction by Chemical Treatments and Essential Oils

Produce	Treatment	Dilutions			Mean +/- S.D (CFU/ml)	ANOVA value	Reduction%
		10^3	10^5	10^8			
Spinach	Acetic acid	6×10^3	3×10^5	1×10^8	$0.0007 \pm 0.0011 \times 10^8$	F =16.72, P=0.0150	99.9%
Okra	Acetic acid	4×10^3	2×10^5	2×10^8	$0.0003 \pm 0.0006 \times 10^8$	F =17.90, P=0.0130	99.9%
Grapes	Acetic acid	3×10^3	2×10^5	2×10^8	$0.0000 \pm 0.0001 \times 10^8$	F =18.42, P=0.0126	100%
Apples	Acetic acid	4×10^3	2×10^5	2×10^8	$0.0003 \pm 0.0006 \times 10^8$	F =17.58, P=0.0138	99.9%
Spinach	Citric acid	5×10^3	2×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.39, P=0.0244	92.9%
Okra	Citric acid	6×10^3	4×10^5	3×10^8	$0.0007 \pm 0.0011 \times 10^8$	F =17.90, P=0.0130	99.8%
Grapes	Citric acid	5×10^3	3×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.27, P=0.0248	92.4%
Apples	Citric acid	4×10^3	3×10^5	2×10^8	$0.0003 \pm 0.0006 \times 10^8$	F =17.58, P=0.0138	99.9%
Spinach	Malic acid	5×10^3	3×10^5	3×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.39, P=0.0244	92.9%
Okra	Malic acid	5×10^3	3×10^5	1×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =13.39, P=0.0215	90.1%
Grapes	Malic acid	4×10^3	3×10^5	1×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.27, P=0.0248	92.4%
Apples	Malic acid	6×10^3	4×10^5	2×10^8	$0.0007 \pm 0.0011 \times 10^8$	F =17.47, P=0.0141	99.8%
Spinach	Lactic acid	5×10^3	4×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.39, P=0.0244	92.9%
Okra	Lactic acid	5×10^3	3×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =13.39, P=0.0215	90.1%
Grapes	Lactic acid	6×10^3	3×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.27, P=0.0248	92.4%
Apples	Lactic acid	7×10^3	5×10^5	3×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.81, P=0.0231	91.0%

Spinach	ASC	3×10^3	2×10^5	2×10^8	$0.0007 \pm 0.0011 \times 10^8$	F =16.72, P=0.0150	99.9%
Okra	ASC	4×10^3	2×10^5	2×10^8	$0.0003 \pm 0.0006 \times 10^8$	F =17.90, P=0.0130	99.9%
Grapes	ASC	4×10^3	4×10^5	2×10^8	$0.0007 \pm 0.0011 \times 10^8$	F =16.56, P=0.0153	99.8%
Apples	ASC	4×10^3	3×10^5	2×10^8	$0.0003 \pm 0.0006 \times 10^8$	F =17.58, P=0.0138	99.9%
Spinach	Potassium permanganate	6×10^3	3×10^5	1×10^8	$0.0003 \pm 0.0006 \times 10^8$	F =16.74, P=0.0150	99.8%
Okra	Potassium permanganate	4×10^3	3×10^5	2×10^8	$0.0003 \pm 0.0006 \times 10^8$	F =17.90, P=0.0130	99.9%
Grapes	Potassium permanganate	5×10^3	2×10^5	1×10^8	$0.0007 \pm 0.0011 \times 10^8$	F =16.56, P=0.0153	99.8%
Apples	Potassium permanganate	6×10^3	5×10^5	2×10^8	$0.0003 \pm 0.0006 \times 10^8$	F =17.58, P=0.0138	99.9%
Spinach	Thyme oil	7×10^3	4×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.39, P=0.0244	92.9%
Okra	Thyme oil	6×10^3	2×10^5	1×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =13.39, P=0.0215	90.1%
Grapes	Thyme oil	5×10^3	3×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.27, P=0.0248	92.4%
Apples	Thyme oil	4×10^3	2×10^5	1×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.81, P=0.0231	91.0%
Spinach	Oregano oil	5×10^3	3×10^5	3×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.39 P=0.0244	92.9%
Okra	Oregano oil	3×10^3	2×10^5	2×10^8	$0.0668 \pm 0.1155 \times 10^8$	F = 7.69, P=0.0501	80.3%
Grapes	Oregano oil	4×10^3	2×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F =12.27, P=0.0248	92.4%
Apples	Oregano oil	5×10^3	2×10^5	2×10^8	$0.0334 \pm 0.0577 \times 10^8$	F= 12.81, P=0.0231	91%

Values represent colony-forming units at three serial dilutions (10^3 , 10^5 , 10^8), along with mean \pm standard deviation of total microbial load. One-way ANOVA was performed to assess statistical differences between treatments ($P < 0.05$ considered significant).

Table 5: Combined Hurdle Decontamination Treatment and Their Efficacy

Produce	Treatment	Dilutions			Mean \pm S.D (CFU/ml)	ANOVA value	Reduction%
		10^3	10^5	10^8			
Spinach	Vinegar (2%) + Refrigeration	4×10^3	2×10^5	2×10^8	$0.0003 \pm 0.0006 \times 10^8$	F= 16.74, P=0.0150	99.9%
Okra	Sodium bicarbonate (2.5%) + Blanching (1-2 min)	4×10^8	3×10^5	2×10^8	$0.0000 \pm 0.0000 \times 10^8$	F= 17.99, P=0.0129	100%
Okra	Lemon juice (4.5%) + Refrigeration	3×10^3	0.4×10^5	0.4×10^8	3.80×10^7	F=17.90, P=0.0130	99.9%
Grapes	Sodium bicarbonate (2.5%) + Refrigeration	3×10^3	2×10^5	2×10^8	$0.0003 \pm 0.0006 \times 10^8$	F= 16.57, P=0.0153	99.9%

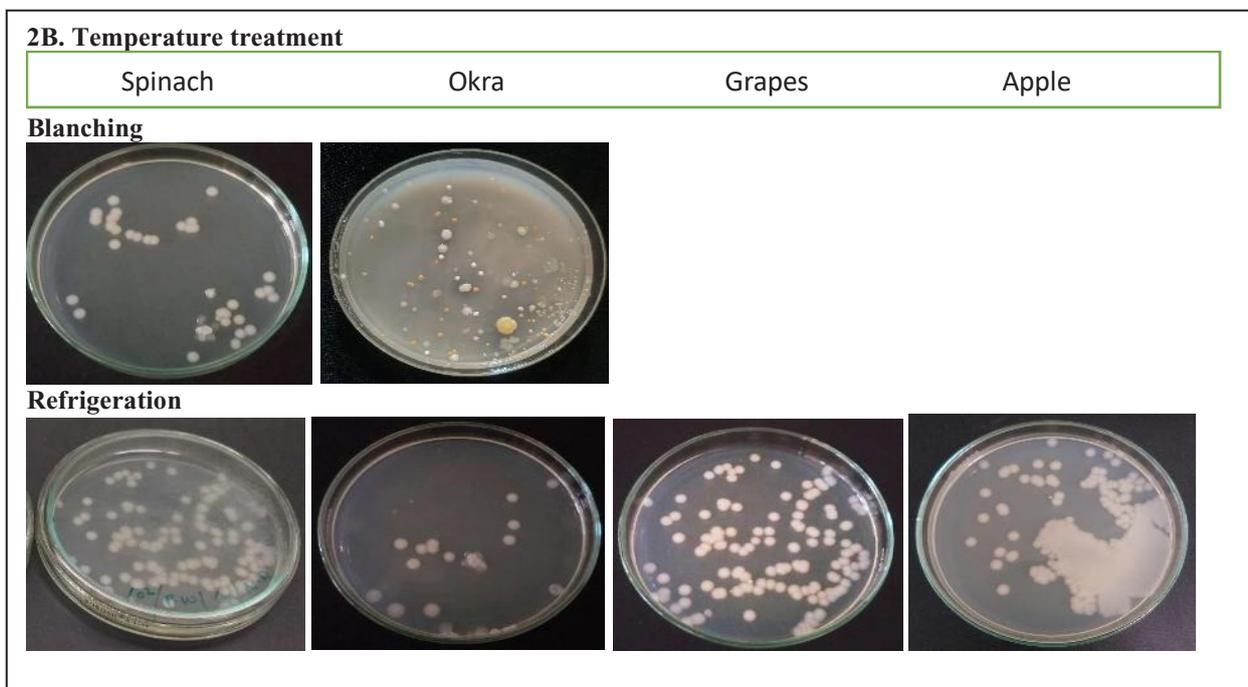
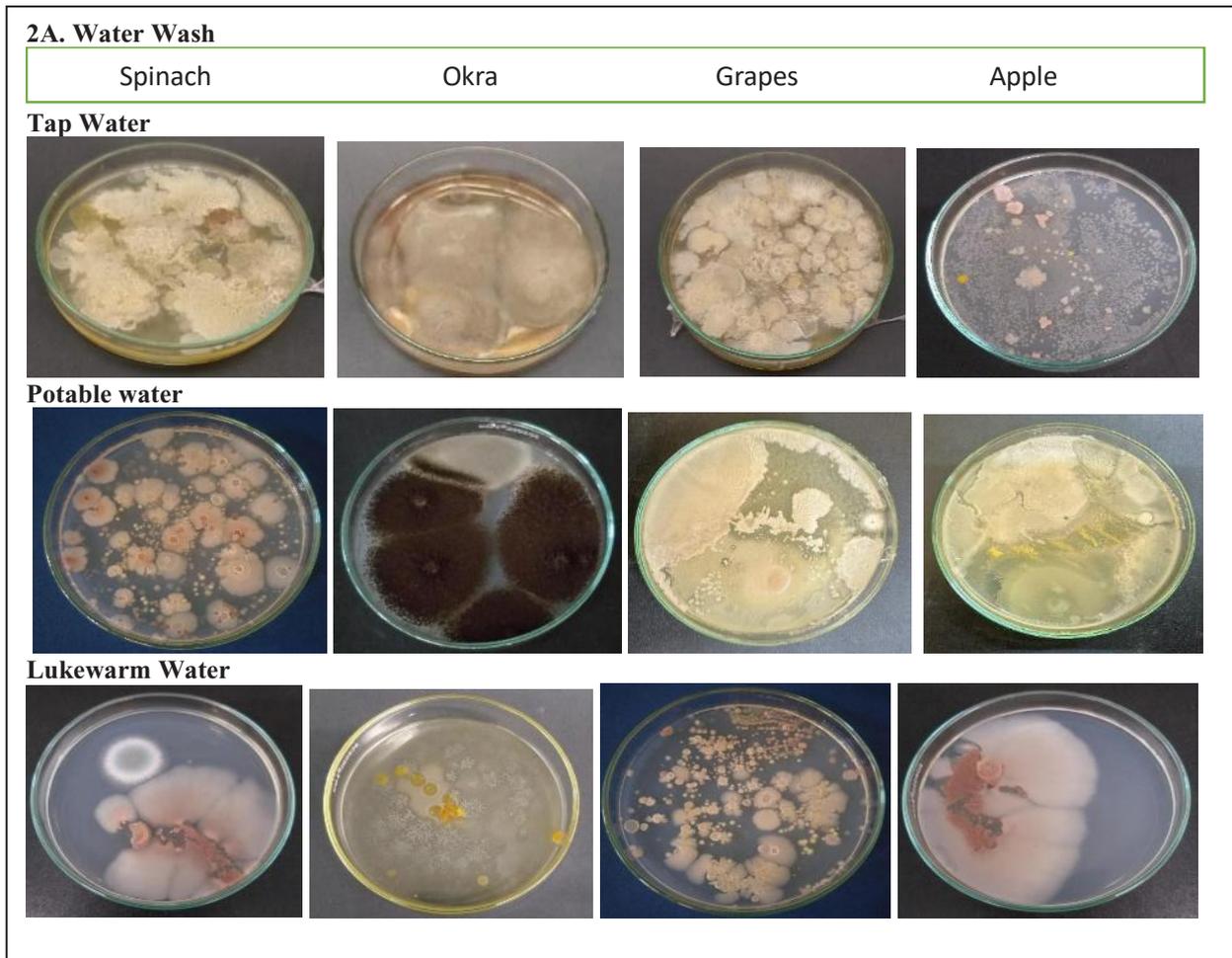
Grapes	Sodium Chloride (2%) + Lukewarm water + Refrigeration	3×10^3	2×10^5	2×10^8	$0.0007 \pm 0.0011 \times 10^8$	F= 16.56, P=0.0153	99.8%
Apples	Sodium bicarbonate (2.5%) + Refrigeration	3×10^3	3×10^5	2×10^8	$0.0007 \pm 0.0011 \times 10^8$	F= 17.47, P=0.141	99.8%

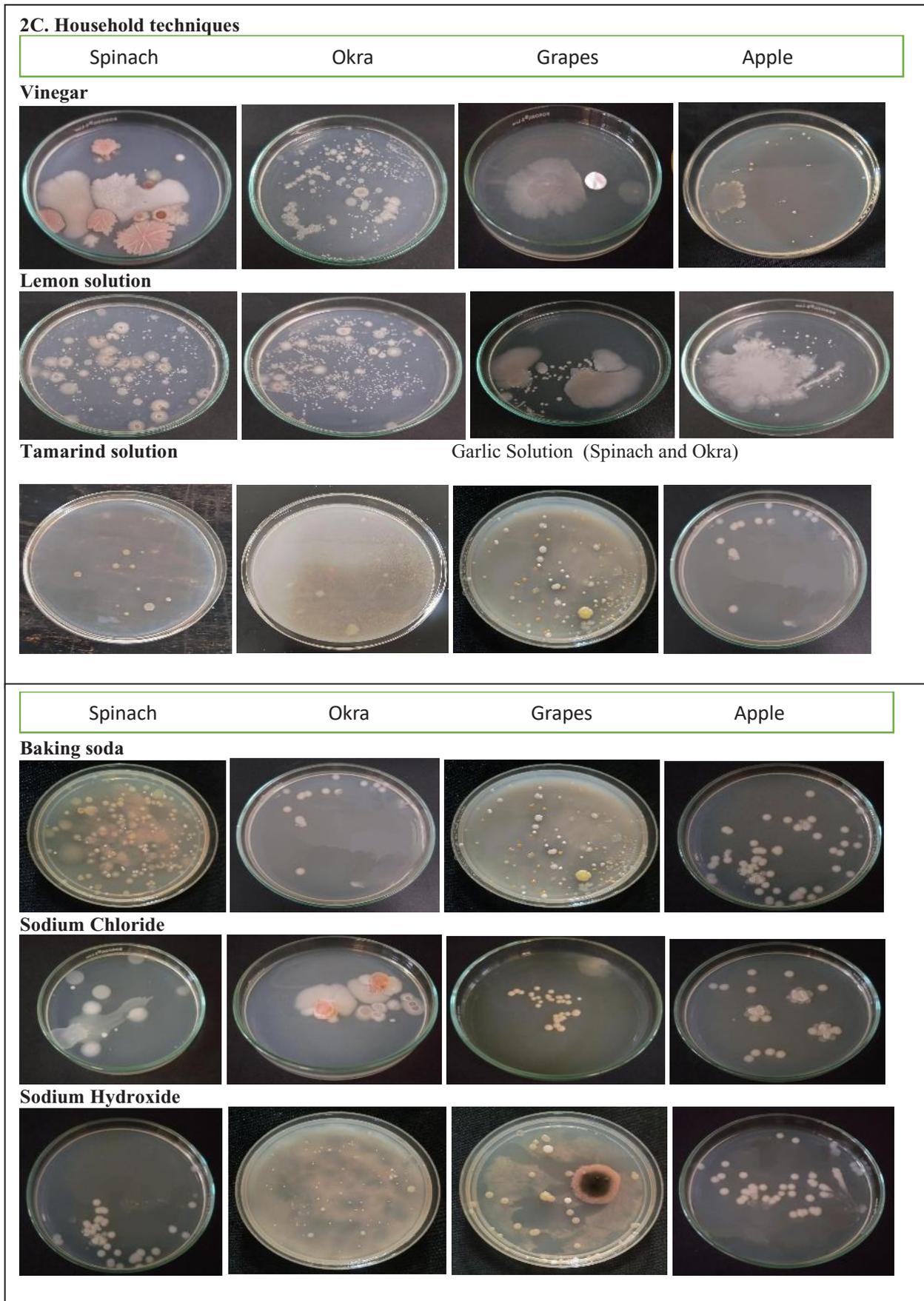
Values represent colony-forming units at three serial dilutions (10^3 , 10^5 , 10^8), along with mean \pm standard deviation of total microbial load. One-way ANOVA was performed to assess statistical differences between treatments ($P < 0.05$ considered significant).

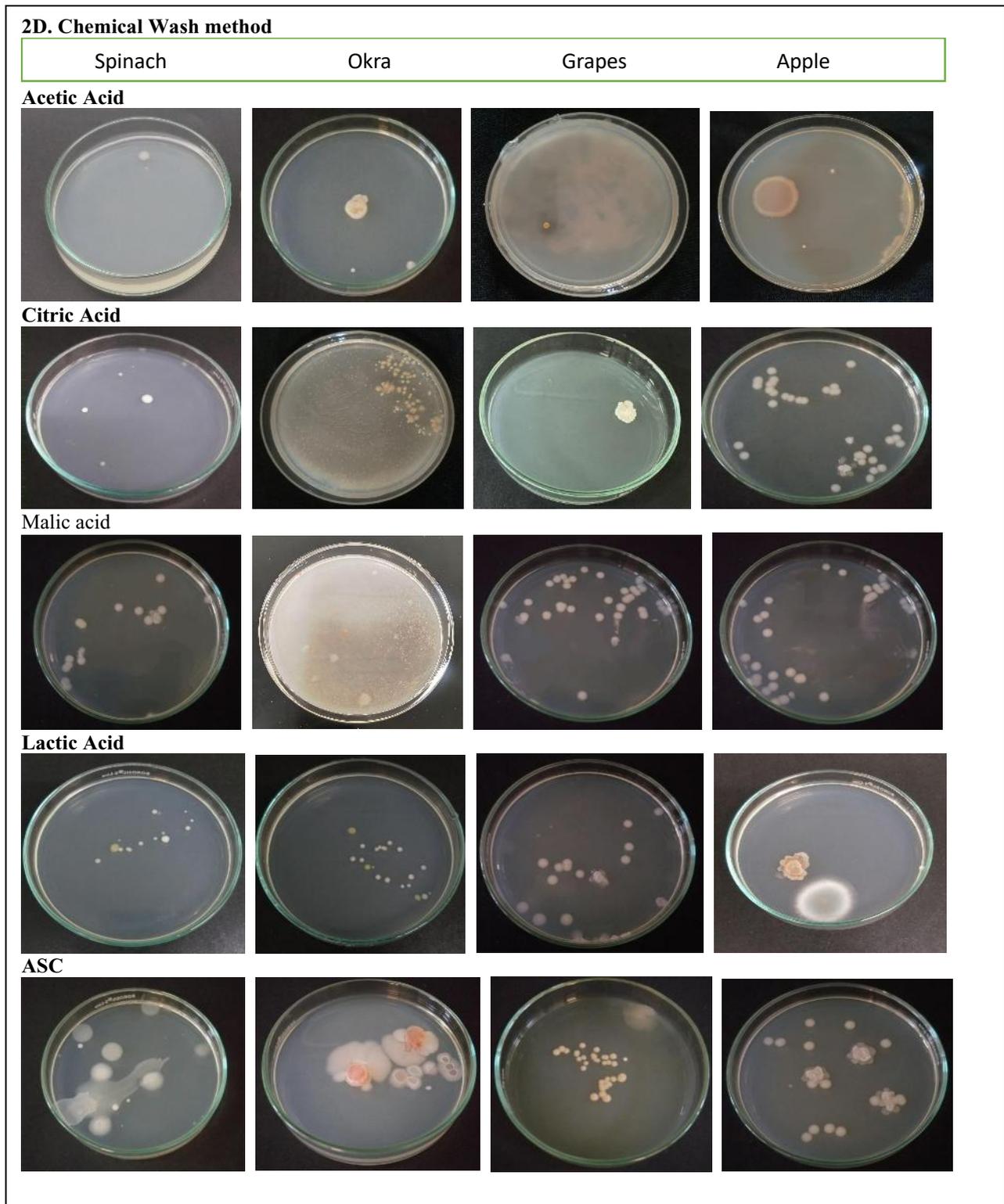
Table 6: Microbial Load in Untreated Control Samples

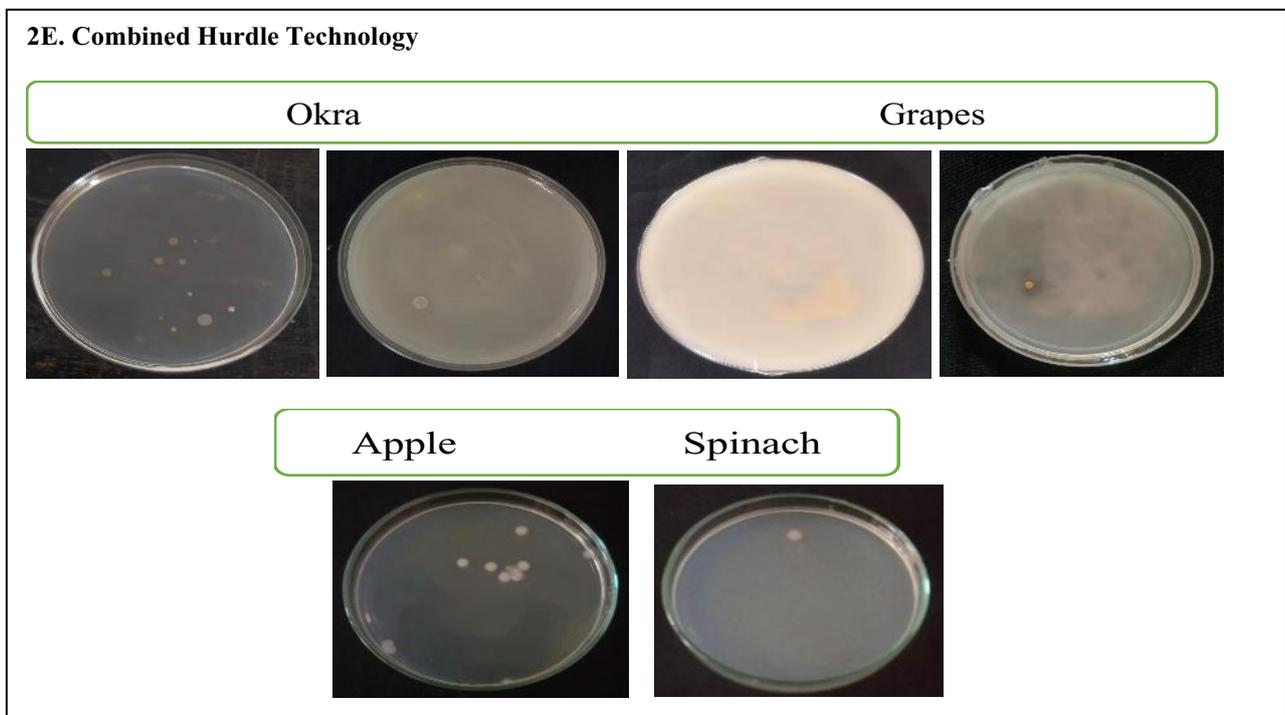
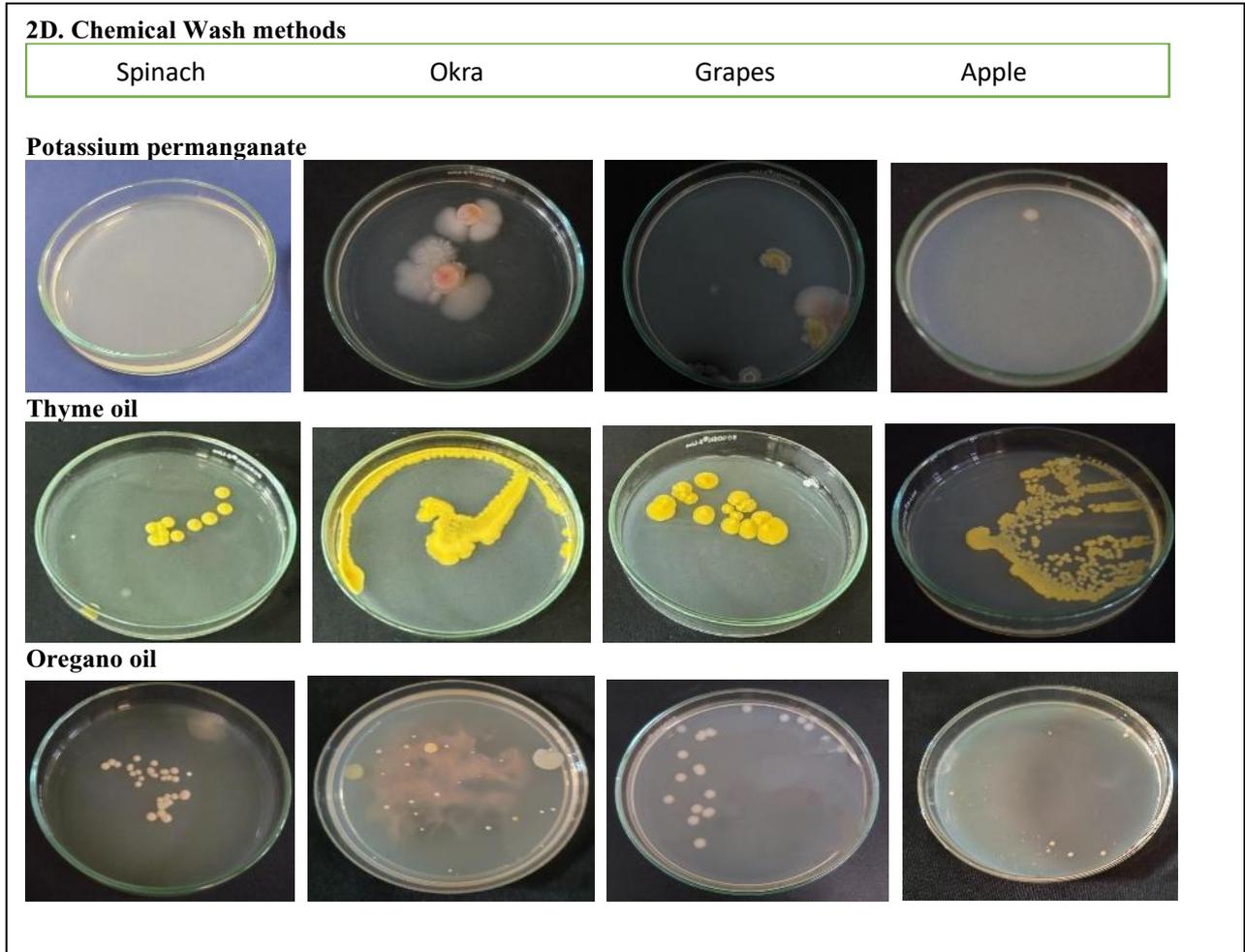
Produce	Treatment	Dilutions			Mean +/- S.D (CFU/ml)
		10^3	10^5	10^8	
Spinach	Control	2.5×10^4	1.7×10^6	1.4×10^9	$4.67 \pm 2.39 \times 10^8$
Okra	Control	2.7×10^4	1.5×10^6	1.0×10^9	$3.34 \pm 1.45 \times 10^8$
Grapes	Control	2.6×10^4	1.7×10^6	1.3×10^9	$4.34 \pm 1.69 \times 10^8$
Apples	Control	2.3×10^4	1.3×10^6	1.1×10^9	$3.67 \pm 1.39 \times 10^8$

Values represent colony-forming units at three serial dilutions (10^3 , 10^5 , 10^8), along with mean \pm standard deviation of total microbial load. One-way ANOVA was performed to assess statistical differences between treatments ($P < 0.05$ considered significant).









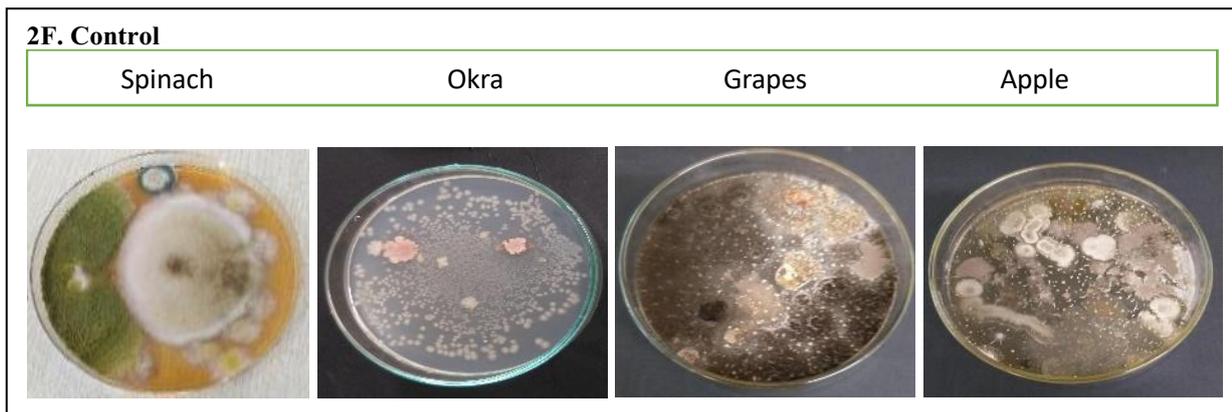


Figure 3: Comparative efficacy of all decontamination approaches used in this study.

- (A) Water wash methods demonstrate moderate removal of loosely attached contaminants.
- (B) Thermal methods, such as blanching and refrigeration, effectively reduce microbial loads by utilizing heat or inhibiting growth.
- (C) Household treatments, including acidic and alkaline solutions, disrupt microbial integrity through bioactive compounds.
- (D) Chemical disinfectants, including organic acids, oxidizers, and essential oils, exhibit strong antimicrobial effects.
- (E) Combined (hurdle) approaches employ multiple strategies and yield the most effective results.
- (F) Control samples display the highest microbial load and serve as the reference for percent reduction.

3.2 Microscopic identification from cultured colonies:

Gram staining was performed on nutrient agar colonies that were chosen based on their shape. A mixed bacterial population was suggested by the observation of both Gram-positive cocci (purple,

clustered) and Gram-negative rods (pink, dispersed). Fungal colonies grew filamentous and pigmented on PDA plates. Septate hyphae were seen by lactophenol cotton blue staining, which is in line with common taxa like *Aspergillus* or *Penicillium*. The morphological diversity points to a typical market-origin microbial profile, even if species-level identification was not attempted.

Table 7: Microscopic characteristics of Selected Plate Culture Colonies

Organism Type	Medium	Colony Appearance	Microscopic Feature (Stain)	Inferred Groups
Bacteria	Nutrient Agar	White, circular, mucoid	Gram-positive cocci (purple clusters)	Possibly <i>Staphylococcus</i> spp.
Fungi	Potato Dextrose Agar	Greenish-black, fuzzy	Septate hyphae (LPCB)	Possibly <i>Aspergillus</i> spp.
Bacteria	Nutrient Agar	Off-white, irregular	Gram-negative rods (pink rods)	Possibly <i>Enterobacteriaceae</i>
Fungi	Potato Dextrose Agar	Bluish-green, powdery	Septate hyphae (LPCB)	Possibly <i>Penicillium</i> spp.

The efficacy of various household decontamination methods was assessed based on their ability to reduce microbial loads across different types of produce, including apples, grapes, okra, and spinach. Among the water-washing techniques, tap water washing reduces microbial load by 20–30%, primarily removing loose surface contaminants. However, this was insufficient for pathogens embedded within the crevices. Potable water washing, which involved

manual rubbing, achieved a slightly better reduction of 30–40%, confirming its limited ability to dislodge pathogens embedded in micro-crevices or attached via biofilms, particularly for textured produce such as spinach and okra, as mentioned in (Table 1; Fig 2A). These results align with earlier findings that loosely attached microbial flora are mostly removed by simple washing [10, 14]. Lukewarm water washing showed further improvement, with reductions ranging

from 40 to 50% due to elevated temperatures aiding the removal of hydrophobic contaminants and biofilms [11]. However, thermal treatment is one of the most effective methods. Blanching reduced microbial loads by 70–85% across all produce types, Refrigeration and freezing, while less effective in eliminating contaminants, reduced microbial loads by 50–60% and slowed microbial proliferation, making them useful for extending shelf life (Table 2; Fig 2B).

The Household treatments demonstrated a higher overall efficacy. A 2% vinegar solution reduced microbial loads by 70–80%, particularly on substrates with porous surfaces, such as grapes and spinach, owing to its acidic properties that disrupt microbial membranes. This is supported by findings, which showed that basic household washes like vinegar and lemon juice may greatly lower *E. coli* infection in salad veggies. Sodium bicarbonate (2.5%) achieved reductions of 72-83%, effectively neutralizing pesticides and disrupting microbial cell walls. Among them, sodium hydroxide (5%) exhibited the microbial reduction at 85%, although extended exposure altered the texture of delicate produce such as grapes, which makes it unsuitable for frequent household use (Table 3; Fig 2C). Lemon juice (4.5%) also showed considerable efficacy, reducing microbial loads by 70–80% while maintaining sensory quality. Sodium chloride (2%) reduced microbial loads by 65–75%, leveraging osmotic effects to inhibit bacterial growth. Tamarind and garlic solutions (5%) also provided moderate reductions, with tamarind achieving 50–65% reductions due to organic acids and garlic achieving 55–70% reductions due to its antimicrobial compounds such as allicin. In contrast, vinegar (acetic acid) and sodium bicarbonate provided a safer balance between practicality and efficacy, lowering microbial loads by as much as 75–80%. This is supported by findings that emphasize the usefulness of these substances in neutralizing pesticide residues as well as microbes [13, 17].

Natural antimicrobials like lemon juice, tamarind extract, and garlic demonstrated moderate effectiveness in reducing microbial loads, typically in the range of 50–70%. Their antimicrobial action is primarily due to bioactive constituents such as organic acids and sulfur-containing compounds like allicin, which are known to disrupt microbial cell membranes and inhibit metabolic pathways. An important advantage of these treatments is their ability to maintain the sensory characteristics, including taste, aroma, and texture, of the fruits and vegetables. This makes them well-suited for frequent use in domestic kitchens where both safety and sensory quality are essential [12].

Across several treatments, advanced chemical washing techniques have shown significant success in reducing microorganisms. Organic acids such as acetic, citric, malic, and lactic acids were successful in lowering microbial loads by 60–80%, with acetic acid continuously showing as the most active among them [9]. By breaking up biofilms and breaking down pesticide residues, potassium permanganate solutions (0.01%–2%) reduce microorganisms by 75–85% [11]. Although moderate discoloration was noted in leafy greens like spinach, as has been shown in investigations on chlorite-based sanitizers, treatment with acidified sodium chlorite (ASC) produced even greater reductions (80–90%) [14]. Even while chemical treatments worked well in this investigation, new non-chemical methods like UV-LED ultrasonic cleaning have shown a lot of promise. Without the use of chemical agents, one study reported a microbial decrease of over 90%, providing a more secure and sustainable option for use in the future. Figure 3 provides a graphic summary of the relative efficacy of each treatment category, illustrating the growing gradient of microbial reduction from water-based to hurdle approaches.

Notably, essential oils like oregano and thyme (at doses of 0.15%–2.1 %) were successful in lowering microbial burdens by 60–70%; nevertheless, their potent aromatic characteristics occasionally changed the treated produce's flavor and scent [10]. Considering their efficacy as antimicrobials, issues including odor retention, expense, and scarcity may prevent their widespread use (Table 4; Fig 2D).

The largest microbial reduction (up to 98%) was obtained in this investigation using hurdle technology treatments, such as vinegar followed by blanching or tamarind with chilling, which outperformed individual techniques (Table 5; Fig E). The findings support previous studies that highlighted the need for combination treatment for maintaining nutritional and sensory quality [13]. They also align with, results that multi-step sanitation was effective when handling produce. Although a few hurdle treatments included light heating (blanching), none resulted in significant color or sensory deterioration, indicating that they may be utilized in household kitchens. The study emphasizes how low-energy methods like blanching or cooling may be used in conjunction with natural, food-grade decontaminants like vinegar or tamarind to achieve nearly total microbe elimination without sacrificing food quality.

When colonies from cultivated plates were stained using basic staining procedures, both Gram-positive and Gram-negative bacteria were found. The idea that open-market food is exposed to a variety of microbial contaminants is supported by this diversity. Similar to

the findings, prior work reported which shows fungal colony examination revealed septate hyphae, indicating contamination by common spoilage fungi such as *Aspergillus* or *Penicillium*. These findings,

while not conclusive, aid in connecting the results of the microbial decrease with the most likely kinds of organisms found on the untreated produce [10, 9].

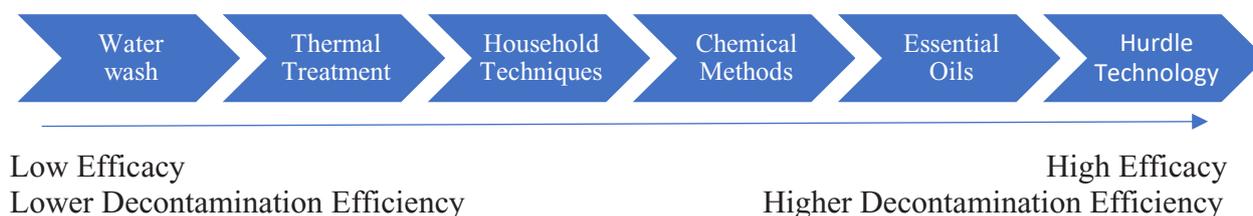


Figure 3: Decontamination Efficiency Gradient for All Treatment Types; From simple water washing (the least effective) to sophisticated hurdle technologies (the most efficient), the graphic shows the rising decontamination efficiency of several treatment categories. Along the arrow, microbial load reduction gets better over time, with hurdle technologies showing the highest level of microbial eradication.

5. CONCLUSION

While water washing is still a common household practice, it was found to be comparatively ineffective against pathogens that are strongly adherent or biofilm-embedded. This aligns with earlier findings, which showed that simple washing only gets rid of surface microorganisms that are weakly attached [10]. But washing with lukewarm water (40°C) increased performance, likely due to thermal softening of biofilms and enhanced solubilization of contaminants. Compared to water alone, chemical disinfectants such as sodium bicarbonate and vinegar (acetic acid) showed noticeably greater efficiency. The pH decrease caused by the acid and the capacity of bicarbonate to neutralize pesticide residues and disrupt microbial membranes are the sources of their antibacterial action. This supports prior findings, which emphasized vinegar's efficacy as an inexpensive, food-safe disinfectant. But even while sodium hydroxide was very successful in reducing microorganisms, its caustic nature and tendency to deteriorate sensory characteristics make it unsuitable for everyday household usage [9]. Among all interventions, Blanching achieved almost complete microbial inactivation, making it the most successful intervention. According to prior findings, its method entails enzyme inactivation and protein denaturation, which eliminates pathogens and increases shelf life [11]. Despite not having a direct bactericidal effect, refrigeration helped to preserve the freshness of vegetables while reducing microbial development [6]. The significance of choosing a context-based approach that is appropriate for the type of product and degree of contamination is emphasized by this study. Combinations of treatments, such as chemical soaking

followed by freezing or blanching, can offer synergistic microbial reduction for leafy or high-risk produce while preserving nutritional integrity. Often referred to as "hurdle technology," this method is becoming more and more popular as a successful multi-barrier approach to food safety [13, 14]. This study adds to the increasing amount of evidence that suggests accessible, affordable, and efficient decontamination techniques for guaranteeing food safety in urban Indian households.

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