RESEARCH ARTICLE

Comparative Efficacy of Household and Bio-Based Washing Agents for Reducing Cypermethrin Residues on Tomatoes (Lycopersicon esculentum)

Muhammad Aziz ul Hassan[1] | Habiba Arooj[2] | Ayesha Noreen[3] | Dr Irfan Suleheria[1]

[1] Sialkot Institute of Science & Technology, Sialkot

[2]Government College University, Faisalabad, Pakistan

[3]Minhaj University Lahore, Pakistan

ABSTRACT

Background: The extensive use of pesticides in intensive vegetable production poses serious food safety concerns, particularly in developing countries where postharvest handling practices are often inadequate. Cypermethrin is widely applied to tomatoes in Pakistan and may persist on produce surfaces at concentrations exceeding recommended safety limits, increasing potential health risks to consumers. **Objective:** This study aimed to compare the effectiveness of selected household washing agents and a natural bio-based washing agent in reducing cypermethrin residues on tomatoes (*Lycopersicon esculentum*). **Methods:** Tomatoes were artificially contaminated with a cypermethrin solution at a concentration of one milliliter per liter. The samples were washed for ten minutes using one percent and two percent solutions of sodium hydrogen carbonate, sodium carbonate, sodium chloride, acetic acid, citric acid, and alfalfa seed extract rich in saponins. Residual cypermethrin levels were determined using spectrophotometric analysis following solvent extraction. **Main Outcome:** The primary outcome measure was the percentage reduction of cypermethrin residues on tomato surfaces after washing. **Results:** Alkaline washing solutions demonstrated the highest residue reduction efficiency. Sodium carbonate achieved the greatest removal, with a maximum reduction of seventy-six point thirty-one percent at the two percent concentration. Sodium hydrogen carbonate and sodium chloride showed moderate effectiveness. Acidic solutions resulted in comparatively lower residue removal, while the alfalfa seed extract exhibited minimal reduction. **Conclusion:** Alkaline household washing agents, particularly sodium carbonate, are highly effective in reducing cypermethrin residues on tomatoes. These findings support the use of simple, accessible washing practices as practical strategies to improve consumer food safety at the household level.

Keywords:

Cypermethrin residues; tomato safety; household washing methods; pesticide; food safety

***Corresponding author**
Muhammad Aziz ul Hassan
mazizulhassan9@gmail.com
Sialkot Institute of Science & Technology, Sialkot
+923333490489

1. INTRODUCTION

Fruits and vegetables are vital components of the human diet, supplying essential micronutrients, antioxidants, and bioactive compounds that contribute to the prevention of chronic diseases. However, in developing countries such as Pakistan, intensive agricultural practices and pest pressures have led to the widespread and often indiscriminate use of pesticides, particularly during the maturation and pre-harvest stages of crops. These practices result in the accumulation of pesticide residues on produce surfaces (1,2), with documented health implications including neurological disorders, endocrine disruption, reproductive toxicity, and carcinogenic effects. Several national surveys have reported that fruits and vegetables in Pakistan frequently exceed Codex Alimentarius maximum residue limits (MRLs), reflecting deficiencies in pesticide management, regulation, and consumer-level mitigation strategies (3).

Among these pesticides, cypermethrin, a synthetic pyrethroid, is one of the most heavily applied insecticides due to its low cost, high efficacy, and broad-spectrum activity against leaf-eating Coleoptera and Lepidoptera (4). Despite its agricultural value, cypermethrin is persistent on crop surfaces and is associated with both acute and chronic human toxicity, including neurotoxicity, oxidative stress, and developmental effects. Reports from Pakistan indicate that cypermethrin residues in tomatoes regularly exceed permissible limits, posing a significant public health concern given the high consumption of tomatoes in raw and minimally processed forms (5).

Household processing, especially washing, is the most accessible approach for reducing pesticide residues before consumption. Previous investigations have shown variable removal efficiencies depending on the physicochemical properties of the pesticide, washing medium, and contact time. Alkaline solutions such as sodium bicarbonate and sodium carbonate have demonstrated notable degradation of pyrethroid residues (6,7), while acidic solutions and simple rinsing exhibit limited effects. In recent years, interest has grown in natural detergents derived from plant sources. Alfalfa (Medicago sativa) seeds contain saponins, amphiphilic molecules with natural surfactant properties that may offer an eco-friendly alternative to synthetic washing solutions. However, evidence regarding their effectiveness in pesticide removal remains scarce (2). Despite extensive literature on pesticide contamination in fruits and vegetables, limited studies have compared the performance of both household chemical washes and plant-based washing agents against cypermethrin residues specifically on tomatoes (1). To address this gap, the present study investigates the effectiveness of conventional washing solutions and alfalfa seed–derived saponins in reducing cypermethrin residues on tomato surfaces, providing practical insights for improving consumer food safety.

2. LITERATURE REVIEW

Pesticides are widely used in agricultural systems to improve crop yield and prevent pest-induced losses. In developing countries such as Pakistan, the intensity and frequency of pesticide application have increased substantially due to rising food demand and pest pressure (2,8). Reports consistently show that fruits and vegetables often retain detectable and sometimes excessive levels of pesticide residues after harvest. Several studies from Pakistan have documented pesticide residues exceeding Codex Alimentarius maximum residue limits (MRLs) in commonly consumed fruits and vegetables, including apples, citrus fruits, grapes, and tomatoes (9,10). This situation is attributed to inappropriate pesticide handling, lack of pre-harvest interval adherence, and inadequate post-harvest washing practices. The persistence of pesticide residues on fresh produce poses significant health risks, including neurological toxicity, endocrine disruption, reproductive impairment, and increased cancer susceptibility (11). Cypermethrin, a type II synthetic pyrethroid, is among the most commonly used insecticides in Pakistan due to its affordability and high effectiveness against a broad range of pests. Although cypermethrin exhibits moderate environmental stability, its hydrophobic nature enables strong adhesion to the waxy cuticle of tomatoes, making removal particularly challenging (12). Previous investigations have shown frequent detection of cypermethrin residues in tomatoes grown and sold across various regions of Pakistan. Both acute and chronic exposure to cypermethrin have been associated with neurobehavioral deficits, oxidative stress, immunotoxicity, and developmental toxicity in humans and experimental models. Given the high per-capita consumption of tomatoes in Pakistan, often in raw or minimally processed forms, the effective removal of cypermethrin residues is an important food safety priority (13,14). Household washing represents the simplest and most accessible method for reducing pesticide residues on fresh produce. Several researchers have evaluated the effects of washing, peeling, cooking, and chemical treatment on the degradation or removal of pesticide residues (10). Tap-water rinsing generally provides limited removal due to the hydrophobicity and cuticular penetration of many pesticides. In contrast, alkaline solutions such as sodium bicarbonate, sodium carbonate, or salt solutions have demonstrated enhanced removal efficiency for pyrethroid and organophosphate residues (7). These solutions can facilitate hydrolysis or weaken pesticide adhesion by altering surface pH. Studies have shown reductions ranging from 40% to over 80% for various pesticides when using sodium carbonate, saltwater, or sonication-assisted washing. Acidic solutions, including citric and acetic acids, also provide some residue reduction, though typically less effectively than alkaline treatments. Thermal processing methods such as cooking, frying, or blanching have shown substantial degradation of certain pesticides, but do not apply to raw consumption (6,9).

Accurate quantification of pesticide residues is essential for evaluating decontamination methods. Numerous analytical techniques have been employed, including GC-MS, GC-ECD, LC-MS/MS, and colorimetric assays. Spectrophotometric methods, such as UV-Vis, based on the formation of chromogenic derivatives, offer cost-effective alternatives suitable for laboratory environments with limited analytical resources. Studies using UV-Vis detection for cypermethrin have demonstrated acceptable linearity, sensitivity, and reproducibility for residual quantification following washing treatments (15,16). Growing consumer interest in environmentally friendly and chemical-free alternatives has encouraged research into plant-derived washing agents. Saponin-rich plants such as alfalfa (Medicago sativa), soapnut, and yucca possess natural surfactant properties due to their amphiphilic structure (17). Saponins can reduce surface tension, form stable foam, and potentially solubilize hydrophobic contaminants. Although saponins are established as natural detergents and exhibit antimicrobial and antioxidant activities, their effectiveness in removing pesticide residues from fresh produce remains largely unexplored. Limited studies suggest that saponins may interact with cuticular lipids, but evidence linking these interactions to pesticide removal efficacy is insufficient (1). While numerous studies have evaluated chemical washing solutions and thermal treatments for pesticide removal, direct comparisons between common household washing agents and natural saponin-based extracts, particularly for cypermethrin on tomatoes, are scarce (4,10). Furthermore, the effectiveness of alfalfa-derived saponins in degrading or solubilizing hydrophobic pesticides has not been specifically investigated. This gap indicates the need for systematic evaluation of both conventional and bio-based washing strategies to support practical, consumer-level interventions for pesticide mitigation (6).

3. MATERIALS AND METHODS

Fresh, externally undamaged tomatoes (Lycopersicon esculentum) were purchased from a local market in Lahore, Pakistan. Alfalfa (Medicago sativa) seeds were procured from a commercial supplier. Analytical-grade solvents and reagents, including ethanol, petroleum ether, acetone, vanillin, sulfuric acid, sodium hydroxide, hydrochloric acid, sodium nitrate, acetic acid, citric acid, sodium hydrogen carbonate, sodium carbonate, and sodium chloride, were obtained from standard laboratory suppliers. Cypermethrin standard (94% purity) was sourced from Four Brothers Pvt. Ltd. (Pakistan), and oleanolic acid standard (95% purity) from Biosynth Carbosynth Ltd. (UK). All experiments were performed using deionized distilled water.

3.1 Extraction and Quantification of Alfalfa Seed Saponins

3.1.1 Saponin Extraction

Saponins were extracted following the method of (18) with modifications. Alfalfa seeds were finely ground using an electric grinder and soaked in 40% ethanol at a 1:5 (w/v) ratio. The mixture was agitated continuously for 48 h at ambient temperature, then centrifuged at 4,000 × g (Eppendorf 5810 R, Germany). The supernatant was collected and concentrated under reduced pressure at 50°C using a rotary evaporator (DAIHAN Scientific, Korea). The crude extract was stored at 4°C until further use.

3.1.2 Saponin Quantification (Vanillin–Sulfuric Acid Method)

Total saponins were quantified using a colorimetric method as described by (18,19). Oleanolic acid standard solutions (100–1600 μg/mL) were prepared in ethanol for calibration. For each assay, 0.25 mL of extract or standard was mixed with 0.25 mL of 8% vanillin solution and 2.5 mL of 72% sulfuric acid. Tubes were heated at 60°C for 15 min in a water bath, cooled for 5 min, and absorbance was measured at 560 nm (UV-1100 spectrophotometer). Total saponins were expressed as mg oleanolic acid equivalents per liter (mg $SE \cdot L^{-1}$).

3.1.3 Qualitative Verification of Saponins

Foam stability was assessed by vigorously shaking 1 mL of saponin extract with 9 mL of distilled water for 10 s. Persistent foam for ≥15 min indicated the presence of saponins.

3.2 Preparation of Cypermethrin Standard and Calibration Curve

3.2.1 Cypermethrin Standard Solutions

A 1 mg/mL stock solution was prepared in ethanol, and serial dilutions (2–30 μg) were used for calibration. Aliquots were hydrolyzed by adding 1 mL of 20% NaOH and incubating at 35°C for 15 min. The reaction mixture was acidified using 1 mL of 3% HCl, followed by the addition of sodium nitrate and 1 mL of 2% aniline solution. After 45 min of color development at 35°C, the volume was adjusted to 25 mL with distilled water. Absorbance was recorded at 535 nm, and a standard curve ($R^2 = 0.9929$) was constructed.

The working saponin washing solutions were standardized based on total saponin content (mg $SE \cdot L^{-1}$). Concentrations were adjusted to deliver equivalent surfactant mass fractions comparable to 1% and 2% chemical washing agents.

3.3 Application of Cypermethrin to Tomatoes

Tomatoes were washed with distilled water, air-dried, and uniformly sprayed with cypermethrin solution (1 mL/L) using a manual spray bottle. Treated tomatoes were air-dried for 1 h at ambient temperature to facilitate pesticide adherence.

3.4 Preparation of Washing Solutions

The following washing solutions were freshly prepared at 1% and 2% (w/v):

- Sodium hydrogen carbonate (baking soda)
- Sodium carbonate
- Sodium chloride
- Citric acid
- Acetic acid
- Alfalfa saponin extract (bio-based washing solution)

Tap water served as the control washing condition.

3.5 Washing Procedure

Contaminated tomatoes were immersed in 400 mL of each washing solution for 10 min with occasional gentle agitation. Samples were then rinsed with 100 mL of distilled water and air-dried at room temperature for 20 min.

3.6 Sample Preparation for Cypermethrin Residue Analysis

Tomato peels were removed, chopped, and weighed (5 g). Residues were extracted using 25 mL of petroleum ether: acetone (1:1, v/v). The mixture was shaken intermittently for 90 min, filtered, and evaporated on a 50°C water bath to approximately 3 mL. The extract was then diluted to 25 mL with ethanol. A 3 mL aliquot was processed using the colorimetric protocol described for cypermethrin standards, and absorbance was read at 535 nm. Residual cypermethrin concentration was calculated using the standard curve equation.

3.7 Statistical Analysis

Data were subjected to one-way ANOVA using Minitab 17. Assumptions of normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test) were verified before analysis. Significant differences were considered at $\alpha = 0.05$. Mean separation was performed using Fisher's LSD test.

4. RESULTS & DISCUSSION

4.1.1 Quantification of Saponins in Alfalfa Seed Extract

The vanillin sulfuric acid colorimetric assay produced a strong linear relationship for oleanolic acid standards (R^2 = 0.9958). The absorbance of the alfalfa extract corresponded to 2185 ± 70 mg SE·L^{-1}, indicating a high saponin content suitable for evaluation as a natural washing agent.

Table 1. Calibration data for oleanolic acid standard curve

CONCENTRATION (µG/ML)	MEAN ABSORBANCE (560 NM)
100	0.116 ± 0.000
250	0.152 ± 0.001
500	0.182 ± 0.000
800	0.229 ± 0.001
1000	0.257 ± 0.000
1200	0.283 ± 0.001
1400	0.321 ± 0.000

4.1.2 Qualitative Verification of Saponins

The foam test resulted in stable, persistent foam for ≥15 minutes, confirming the presence of surfactant compounds (saponins) in the extract.

4.1.3 Cypermethrin Calibration Curve and Spectrophotometric Response

The cypermethrin calibration curve exhibited a linear response (R^2 = 0.9929). Final absorbance values were obtained after blank subtraction.

Table 2. Absorbance values for the cypermethrin standard curve (535 nm)

CONCENTRATION (µG/ML)	FINAL ABSORBANCE (MEAN ± SD)
5	0.078 ± 0.000
10	0.128 ± 0.001
15	0.177 ± 0.001
20	0.251 ± 0.001
25	0.280 ± 0.001
30	0.337 ± 0.001
35	0.419 ± 0.000
40	0.446 ± 0.001

The regression equation from the calibration curve was used to compute residual cypermethrin concentrations in treated samples.

4.1.4 Effectiveness of Washing Solutions (1% Concentration)

Significant differences were observed among washing treatments ($p < 0.0001$). Tap water removed 33.49 ± 0.07% of cypermethrin. Among household solutions, sodium carbonate (56.41 ± 0.10%) demonstrated the greatest removal efficiency, followed by sodium hydrogen carbonate (37.96 ± 0.10%) and sodium chloride (35.15 ± 0.05%). Acidic solutions exhibited comparatively lower removal efficiency. Saponin extract removed only 2.04 ± 0.09%, indicating minimal ability to detach or degrade cypermethrin at this concentration.

Table 3. Cypermethrin removal (%) using 1% washing solutions

WASHING TREATMENT	PH	REMOVAL (%) (MEAN ± SD)
TAP WATER (CONTROL)	~7.0	33.49 ± 0.07
SODIUM HYDROGEN CARBONATE	8.1	37.96 ± 0.10
CITRIC ACID	2.7	21.26 ± 0.05
ACETIC ACID	2.9	23.50 ± 0.06
SODIUM CHLORIDE	6.7	35.15 ± 0.05
SODIUM CARBONATE	11.3	56.41 ± 0.10
ALFALFA SAPONIN EXTRACT	5.5	2.04 ± 0.09

4.1.5 Effectiveness of Washing Solutions (2% Concentration)

Increasing the concentration improved the removal efficiency of all solutions except saponins. The highest removal was again observed for sodium carbonate (76.31 ± 0.05%), followed by sodium hydrogen carbonate (51.17 ± 0.05%) and sodium chloride (45.05 ± 0.03%). Acetic acid performed better than citric acid at equal concentrations. Saponins removed only 3.4 ± 0.08%, supporting the conclusion that saponin–pesticide interactions do not promote detachment of cypermethrin residues from tomato surfaces.

Table 4. Cypermethrin removal (%) using 2% washing solutions

WASHING TREATMENT	PH	REMOVAL (%) (MEAN ± SD)
TAP WATER (CONTROL)	~7.0	33.49 ± 0.07
SODIUM HYDROGEN CARBONATE	8.1	51.17 ± 0.05
CITRIC ACID	2.7	28.06 ± 0.04
ACETIC ACID	2.9	37.09 ± 0.04
SODIUM CHLORIDE	6.7	45.05 ± 0.03
SODIUM CARBONATE	11.3	76.31 ± 0.05
ALFALFA SAPONIN EXTRACT	5.5	3.40 ± 0.08

4.2 DISCUSSION

The present study evaluated the effectiveness of household washing solutions and alfalfa seed–derived saponin extract in reducing cypermethrin residues on tomatoes. Overall, the findings demonstrated that washing significantly lowers pesticide residues; however, the extent of removal depends strongly on the pH, chemical nature, and functional properties of the washing medium. Alkaline solutions, particularly sodium carbonate, exhibited the greatest removal efficacy, while plant-based saponins showed minimal impact. These results are aligned with previous studies on pyrethroid behavior and support the conclusion that residue–cuticle interactions require specific chemical conditions for effective removal. Sodium carbonate showed the highest residue removal at both concentrations (56.41% at 1%

and 76.31% at 2%), which can be attributed to its strong alkaline pH and capacity to promote hydrolysis of pyrethroid esters. Pyrethroids such as cypermethrin are susceptible to alkaline degradation, where high pH disrupts the ester bond and reduces lipid-soluble pesticide adhesion. Similar findings have been reported by (20,21), who demonstrated that alkaline washing solutions accelerate hydrolytic breakdown and facilitate pesticide detachment from fruit surfaces. Sodium hydrogen carbonate also demonstrated moderate removal, which is consistent with its weaker alkalinity and buffering action. The improved performance of alkaline solutions with increased concentration corroborates the pH-dependent degradation mechanism of pyrethroids. Citric and acetic acid exhibited comparatively lower removal efficiencies (21–37%), indicating that acidic solutions are less effective for hydrophobic pesticide removal. Cypermethrin adheres strongly to the waxy cuticular layer of tomatoes, and acidic media lack the structural capability to chemically degrade or solubilize such nonpolar compounds. Although weak organic acids can aid in removing surface debris, their effect on pyrethroid detachment appears limited. Previous research similarly reports poor removal of pyrethroids by acidic solutions, further supporting the specificity of alkaline hydrolysis for this group of pesticides (4). Sodium chloride demonstrated notable removal (35–45%), exceeding that of citric acid and acetic acid. Salt solutions may enhance pesticide removal by improving ionic strength, weakening pesticide–cuticle interactions, or facilitating surface abrasion. Studies by (9) suggested that salt ions can disrupt electrostatic interactions between pesticide molecules and plant waxes. However, the absence of chemical degradation pathways limits their overall efficacy compared to alkaline solutions. Despite its surfactant properties, the alfalfa saponin extract removed only 2–3% of residues. This minimal effect suggests that the hydrophobicity and strong lipophilic affinity of cypermethrin exceed the solubilization capacity of saponins at the concentrations tested. Saponins typically reduce surface tension and can emulsify oils, yet their ability to extract strongly bound pesticide residues depends on molecular compatibility. The findings contrast with expectations based on saponin activity in detergent formulations, indicating that bio-based surfactants may require higher concentrations or formulation enhancement (e.g., pH adjustment, enzymatic augmentation) to be effective. Limited literature exists on saponin-mediated pesticide removal, highlighting this as an emerging area with unexplored potential (22). The limited removal efficiency of saponins may partly be attributed to the acidic pH (5.5) of the extract. Pyrethroids such as cypermethrin undergo alkaline hydrolysis, and therefore, the absence of alkaline conditions likely limited degradation-mediated removal. (4,6). Across all treatments, increasing concentration from 1% to 2% improved pesticide removal. This trend is consistent with concentration-response relationships reported in other washing studies, where higher solute availability enhances chemical reactivity, surfactant action, and overall cleaning efficiency. The small increase observed for saponins reinforces the conclusion that their mechanism is poorly matched to the chemical characteristics of cypermethrin.

5. CONCLUSION

This study demonstrated that the effectiveness of washing treatments for removing cypermethrin residues from tomatoes varies significantly with the chemical properties of the washing medium. Among all treatments evaluated, sodium carbonate exhibited the highest removal efficiency at both 1% and 2% concentrations, confirming the strong role of alkaline hydrolysis in degrading pyrethroid residues. Sodium hydrogen carbonate and sodium chloride also provided moderate removal, whereas acidic solutions such as citric and acetic acid were less effective due to their limited interaction with the hydrophobic pesticide structure. Despite its natural surfactant properties, the alfalfa seed saponin extract showed minimal ability to remove cypermethrin, indicating that bio-based surfactants alone may not provide sufficient residue mitigation for highly lipophilic pesticides. The findings highlight the practical relevance of alkaline household washing agents as accessible and cost-effective interventions to enhance consumer food safety. Adoption of these methods is particularly important in regions where pesticide misuse and inadequate pre-harvest intervals contribute to elevated residue levels on fresh produce. Future research should explore optimized formulations of natural surfactants, evaluate real-field contamination scenarios, and employ advanced chromatographic techniques to characterize degradation pathways and metabolites. Overall, this study contributes to improving evidence-based recommendations for reducing pesticide exposure through simple, consumer-level practices.

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