



REVIEW ARTICLE

# Pesticide residues in leafy vegetables: From detection to detoxification

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## Abstract

Leafy vegetables constitute a vital component of human diets worldwide owing to their rich nutritional profile, including essential vitamins, minerals, dietary fibre and bioactive compounds. However, their cultivation often involves intensive pesticide application, which may leave harmful residues on edible tissues. The persistence of these residues poses significant public health concerns due to their potential for acute and chronic toxicity. This review compiles and synthesises current research findings on pesticide residues in major leafy vegetables, including lettuce, cabbage, spinach, amaranthus, curry leaf, celery, rocket and parsley. Special emphasis is placed on residue monitoring studies across different countries, on dissipation patterns under varying agroecological conditions and on household- or field-level decontamination strategies. This review highlights that multiple residues often exceed maximum residue limits (MRLs), raising risks for consumers. Dissipation studies show that half-lives vary widely depending on the chemical, crop and environmental conditions. At the same time, effective decontamination requires tailored interventions such as washing, cooking and using salt, vinegar or commercial washes. Overall, reducing pesticide residues in leafy vegetables requires integrated monitoring approaches, improved agricultural practices and scientifically validated decontamination methods to safeguard consumer health.

**Keywords:** decontamination; dissipation; leafy vegetables; pesticide residues; public health

## Introduction

Leafy vegetables are an integral part of human nutrition worldwide, accounting for nearly 2 % of global vegetable consumption in raw, boiled or steamed forms (1). Varieties such as parsley, rocket, lettuce and spinach are among the most widely consumed vegetables today (2). In Ghana, common leafy vegetables include spinach (*Spinacia* spp.), amaranthus (*Amaranthus* spp.), roselle leaves (*Hibiscus* spp.) and lettuce (*Lactuca* spp.), which form a major part of the traditional diet (3). In India, *Amaranthus tricolor* L. is the most extensively cultivated leafy type, while *Amaranthus blitum* L. and *Amaranthus tristis* L. are also grown, particularly in the southern regions, where they serve as staple greens (4). A balanced adult diet includes approximately 100 g of green leafy vegetables per day (5).

Leafy vegetables are versatile in culinary practices, consumed fresh in salads, cooked, or even dried for year-round availability. The demand for these vegetables has increased sharply in recent years due to the global shift towards healthier eating habits (6). These vegetables are valued for their rich nutritional composition, being important sources of phytochemicals, carbohydrates, proteins, dietary fibre, minerals such as potassium (K), calcium (Ca), magnesium (Mg), phosphorous (P), iron (Fe), zinc (Zn) and manganese (Mn), as well as vitamins A, B-complex, C and carotenoids (7). However, their cultivation is also associated with

risks from toxic agrochemicals, particularly pesticides (8).

Pesticide residue levels in food commodities not only pose direct risks to human health but also have significant consequences for international trade (9). If pesticide residues contribute to > 50 % of the acute reference dose (ARfD) and > 4 % of the acceptable daily intake (ADI) in South African wheat, they pose both acute and chronic health risks to consumers (10). Pesticide residues on leafy vegetables are a growing public health concern due to both acute and chronic health risks, which may include cardiovascular disease, neurological toxicity, developmental impairment, genetic mutations, birth defects and cancer. High levels of pesticide residues may be detrimental to consumers, since the whole plant is edible (11). Considering the nutritional importance of leafy vegetables, it is critical to evaluate and manage the risks associated with pesticide residues. Analytical techniques such as QuEChERS (quick, easy, cheap, effective, rugged and safe), developed to have become widely used for monitoring pesticide residues due to their simplicity, efficiency and low cost (12). As maximum residue limits (MRLs) differ among countries and regulatory authorities, the MRL values presented in this review correspond to the standards cited in the respective studies (Table 1).

Extensive literature indicates that food processing generally results in substantial reductions in pesticide residues, particularly through common operations such as washing, peeling and cooking

**Table 1.** List of pesticide residues above the maximum residue limit (MRL) in leafy vegetables

| Sl. No. | Crop       | Pesticide           | Detected residue level (mg kg <sup>-1</sup> ) | Maximum residue limit (MRL) (mg kg <sup>-1</sup> ) | References |
|---------|------------|---------------------|-----------------------------------------------|----------------------------------------------------|------------|
| 1.      | Lettuce    | Chlorpyrifos        | 1.600                                         | 0.500                                              | (16)       |
| 2.      |            |                     | 2.800                                         | 0.500                                              | (15)       |
| 3.      |            | Methoxychlor        | 0.023                                         | 0.010                                              | (18)       |
| 4.      |            | Dieldrin            | 0.035                                         | 0.010                                              |            |
| 5.      |            | Chlorpyrifos        | 0.220                                         | 0.010                                              |            |
| 6.      |            | Lufenuron           | 1.060                                         | 0.200                                              | (84)       |
| 7.      |            | Lambda-cyhalothrin  | 0.900                                         | 0.020                                              |            |
| 8.      |            | Dimethoate          | 3.110                                         | 0.020                                              |            |
| 9.      |            | Diazinon            | 0.080                                         | 0.010                                              | (19)       |
| 10.     |            | Chlorpyrifos        | 1.270                                         | 0.100                                              |            |
| 11.     |            | Lindane             | 0.100                                         | 0.010                                              |            |
| 12.     | Cabbage    | Methoxychlor        | 0.023                                         | 0.010                                              | (18)       |
| 13.     |            | Dieldrin            | 0.035                                         | 0.01                                               |            |
| 14.     |            | Dimethoate          | 0.202                                         | 0.02                                               | (24)       |
| 15.     |            | Chlorpyrifos        | 2.860                                         | 0.50                                               | (21)       |
| 16.     |            | Monocrotophos       | 0.280                                         | 0.20                                               | (25)       |
| 17.     |            | Chlorpyrifos        | 0.080                                         | 0.05                                               |            |
| 18.     |            | Dimethoate          | 0.202                                         | 0.02                                               | (24)       |
| 19.     | Amaranthus | Chlorpyrifos        | 1.535                                         | 0.05                                               | (27)       |
| 20.     |            | Endosulfan ether    | 0.184                                         | 0.007                                              | (29)       |
| 21.     |            | Lindane             | 0.504                                         | 0.02                                               |            |
| 22.     |            | Heptachlor          | 0.502                                         | 0.01                                               | (28)       |
| 23.     |            | Profenofos          | 3.655                                         | 1.00                                               |            |
| 24.     |            | Imidacloprid        | 0.520                                         | 0.5                                                | (31)       |
| 25.     | Spinach    | Deltamethrin        | 0.908                                         | 0.5                                                |            |
| 26.     |            | Chlorpyrifos        | 0.320                                         | 0.01                                               |            |
| 27.     |            | Lufenuron           | 1.470                                         | 0.2                                                | (84)       |
| 28.     |            | Indoxacarb          | 3.670                                         | 1.0                                                |            |
| 29.     |            | Bifenthrin          | 0.013                                         | 0.01                                               |            |
| 30.     |            | Clothianidin        | 0.032                                         | 0.01                                               |            |
| 31.     |            | Diuron              | 0.036                                         | 0.01                                               |            |
| 32.     | Rocket     | Dinocap             | 0.041                                         | 0.02                                               |            |
| 33.     |            | Hexythiazox         | 0.018                                         | 0.01                                               |            |
| 34.     |            | Imidacloprid        | 0.058                                         | 0.01                                               |            |
| 35.     |            | Triadimenol         | 0.061                                         | 0.01                                               |            |
| 36.     |            | Thiamethoxam        | 0.202                                         | 0.01                                               | (2)        |
| 37.     |            | Pyridaben           | 0.236                                         | 0.01                                               |            |
| 38.     |            | Penconazole         | 0.013                                         | 0.01                                               |            |
| 39.     | Parsley    | Oxamyl              | 0.040                                         | 0.01                                               |            |
| 40.     |            | Chlorpyrifos-methyl | 0.899                                         | 0.01                                               |            |
| 41.     |            | Hexaconazole        | 1.501                                         | 0.02                                               |            |
| 42.     |            | Malathion           | 0.991                                         | 0.02                                               |            |
| 43.     |            | Pymetrozine         | 1.351                                         | 0.05                                               |            |

(13). Consequently, identifying simple and cost-effective approaches to minimise dietary exposure to harmful pesticides is especially critical for low-income populations (14). A wide range of household-level decontamination strategies, such as washing with clean water, salt or detergent solutions; peeling; blanching; boiling and other thermal treatments, have been explored for their ability to degrade or remove pesticide residues. Understanding the relative efficacy of these easily adoptable practices is essential for developing practical recommendations that can significantly enhance food safety for consumers at all economic levels. The present review focuses on pesticide residue monitoring in leafy vegetables, residue dissipation and half-life and decontamination methods for residue removal, thereby providing a comprehensive overview of these interconnected aspects that have not been collectively addressed in earlier reviews.

### Monitoring of pesticide residues in leafy vegetables

#### Lettuce

Several studies have demonstrated the presence of multiple pesticide residues in lettuce, often exceeding MRLs. Previous records reported that 45 lettuce samples were contaminated with chlorpyrifos and profenofos residues. The mean concentration of chlorpyrifos residues reached 2.8 mg kg<sup>-1</sup>, well above acceptable safety limits (15). The lettuce samples collected in 2005 from Kumasi, Tamale and Accra contained residues of lindane, endosulfan, chlorpyrifos, lambda-cyhalothrin and dichlorodiphenyltrichloroethane (DDT) with most concentrations exceeding the Food and Agriculture Organization (FAO) of the United Nations/World Health Organization (FAO/WHO)-recommended MRLs. Among these, chlorpyrifos was the most

prevalent, detected in 78 % of the samples at an average concentration of  $1.6 \text{ mg kg}^{-1}$ , which was more than three times higher than the permissible limit of  $0.5 \text{ mg kg}^{-1}$  (16). The residues of mevinphos ( $0.002 \text{ mg kg}^{-1}$ ), azinophos ( $0.007 \text{ mg kg}^{-1}$ ), phosmet ( $0.018 \text{ mg kg}^{-1}$ ), tetramethrin ( $0.054 \text{ mg kg}^{-1}$ ), allethrin ( $0.020 \text{ mg kg}^{-1}$ ) and carbofuran ( $0.003 \text{ mg kg}^{-1}$ ) in lettuce collected from Saudi Arabia (17). The contamination of lettuce samples also documented in Ghana. While multiple pesticide residues were identified, methoxychlor and dieldrin exceeded MRLs. Mean concentrations of methoxychlor and dieldrin were  $0.023 \text{ mg kg}^{-1}$  and  $0.035 \text{ mg kg}^{-1}$  respectively, both below the recommended standard of  $0.01 \text{ mg kg}^{-1}$  (18). In another Ghanaian study, reported alarmingly high levels of pesticide residues in lettuce. The study revealed that lambda-cyhalothrin, dimethoate, diazinon and chlorpyrifos exceeded MRLs by 1550–4400 %, 14750–15,450 %, 400–700 % and 1140–1170 % respectively (19). The presence of pesticide residues in lettuce collected in Henan province, China, with lambda-cyhalothrin ( $0.407 \text{ mg kg}^{-1}$ ) detected in 21.10 % of the samples analysed (20).

### Cabbage

Pesticide contamination in cabbage has been widely reported, with several studies documenting residues exceeding MRLs. The profenofos residues in cabbage exceeded the MRL (15). The occurrence of deltamethrin ( $0.529 \text{ mg kg}^{-1}$ ), chloroneb ( $0.005 \text{ mg kg}^{-1}$ ) and benomyl ( $0.016 \text{ mg kg}^{-1}$ ) residues were documented in cabbage samples of Saudi Arabia (17). In Ghana, 68 % of the cabbage samples analysed were contaminated with different pesticides. Residues of lindane ( $0.100 \text{ mg kg}^{-1}$ ), methoxychlor ( $0.023 \text{ mg kg}^{-1}$ ) and dieldrin ( $0.035 \text{ mg kg}^{-1}$ ) were all higher than the standard value of  $0.01 \text{ mg kg}^{-1}$  (18). Sapbamrer and Hongsibsong, in Thailand, found that 12.5 % of Chinese cabbage samples were contaminated with chlorpyrifos, with an average residue level of  $2.86 \text{ mg kg}^{-1}$ , far above the recommended  $0.5 \text{ mg kg}^{-1}$  (21). Similarly, the dimethoate residues in cabbage were 550–700 % above the recommended MRL (19). The contamination of Chinese cabbage with multiple pesticides, with residues exceeding MRLs by 3.6 % for methamidophos, 3.6 % for dichlorvos, 7.1 % for o-methoate, 10.7 % for phorate, 3.6 % for diazinon and 7.1 % for parathion (22). A three-year monitoring study (2010–12) conducted in Accra analysed 252 samples each of cabbage and lettuce. The study reported that residues of deltamethrin, cypermethrin, cyfluthrin, pirimiphos-methyl,  $\alpha$ -Endosulfan, p,p'-DDE, bifenthrin and chlorpyrifos frequently exceeded the MRLs (23). Further, documented the presence of lambda-cyhalothrin and cypermethrin ( $0.054 \text{ mg kg}^{-1}$ ) in 7.14 % of Chinese cabbage samples (20). In Nigeria, dimethoate residues also detected at  $0.202 \text{ mg kg}^{-1}$ , which exceeded the European Food Safety Authority (EFSA) limit of  $0.02 \text{ mg kg}^{-1}$  (24).

The contamination were measured in Rajasthan, India, measured contamination in 28 % of cabbage samples. Monocrotophos residues were recorded at levels 5.12 % higher than the MRL, while chlorpyrifos residues were 2.56 % above the standard limit (25). Cabbage samples collected from various markets across Kerala, India, were tested for residues of chlorpyrifos, profenophos, quinalphos, metalaxyl, lambda-cyhalothrin, acephate, monocrotophos, clothianidin, imidacloprid and thiamethoxam under the 'Safe to Eat' project of Kerala (26).

### Amaranthus

Residues in *Amaranthus* have been a focus of several studies. In Bangladesh, reported three out of 27 amaranthus samples were contaminated with chlorpyrifos, with levels as high as  $1.54 \text{ mg kg}^{-1}$ ,

exceeding the standard MRL of  $0.05 \text{ mg kg}^{-1}$  (27). The detection of 19 pesticide residues in *Amaranthus spinosus* L. samples from Donga (Nigeria), including cyclodienes, cyclohexanes, DDT, dichlorodiphenyldichloroethane (DDD), dicofol, perthane, endosulfan, pentachlorobenzene, mirex, toxaphene, hexachlorobenzene, methoxychlor, aldrin, dieldrin,  $\alpha$ -HCH,  $\beta$ -HCH,  $\gamma$ -HCH, chlordane and heptachlor. The mean concentrations of all residues exceeded FAO and WHO MRLs (8). Similarly, the residues of lindane and heptachlor in *Amaranthus* leaves in Nigeria were above permissible MRLs (28). In Nigeria, detected residues of dieldrin, endosulfan, methoxychlor and endosulfan ether were detected in green amaranth, indicating the presence of persistent organochlorine pesticides in this leafy vegetable (29). In Nigeria, imidacloprid was detected at  $0.06 \text{ mg kg}^{-1}$  in amaranthus samples, which was within the Codex Alimentarius Commission's MRL of  $0.06 \text{ mg kg}^{-1}$  (24).

*Amaranthus* samples sourced from multiple markets in Kerala revealed the presence of several pesticide residues, including chlorpyrifos, cypermethrin, fenvalerate, lambda-cyhalothrin, flubendiamide, thiamethoxam, carbendazim, imidacloprid, tebuconazole, quinalphos and ethion (26). Among 20 amaranthus samples, 13 contained quinalphos residues ranging from  $0.04$ – $1.20 \text{ mg kg}^{-1}$ , with 4 exceeding the European Union maximum residue limit (EU-MRL) of  $0.05 \text{ mg kg}^{-1}$ . Chlorpyrifos was present in three samples, all above the EU-MRL. Profenofos, bifenthrin, ethion and fenvalerate were detected in single samples, each exceeding the EU-MRL. Lambda-cyhalothrin and cypermethrin were also detected, but were below the EU-MRL (30).

### Spinach

Residue monitoring in spinach has revealed contamination with a wide spectrum of pesticides. Spinach samples from Egypt contained dimethoate and profenofos residues exceeding MRLs (15). Spinach samples from Saudi Arabia contained residues of endosulfan ( $0.019 \text{ mg kg}^{-1}$ ), phosmet ( $0.013 \text{ mg kg}^{-1}$ ), permethrin ( $0.065 \text{ mg kg}^{-1}$ ), linuron ( $0.004 \text{ mg kg}^{-1}$ ), pirimiphos-ethyl ( $0.018 \text{ mg kg}^{-1}$ ), dimethoate ( $0.013 \text{ mg kg}^{-1}$ ) and cyfluthrin ( $0.25 \text{ mg kg}^{-1}$ ), indicating widespread pesticide contamination in this leafy vegetable (17). Carbaryl residues were also detected in spinach from Saudi Arabia, with concentrations reaching  $0.92 \text{ mg kg}^{-1}$  (1). At Bogor Agricultural University in Indonesia, residues of profenofos, imidacloprid and deltamethrin were detected, exceeding the national maximum benchmark residue (BMR). Profenofos residues were  $3.6546 \text{ mg kg}^{-1}$  compared to a BMR of  $1 \text{ mg kg}^{-1}$ , imidacloprid residues reached  $0.5195 \text{ mg kg}^{-1}$  against a BMR of  $0.5 \text{ mg kg}^{-1}$  and deltamethrin residues were  $0.9084 \text{ mg kg}^{-1}$ , exceeding the BMR of  $0.5 \text{ mg kg}^{-1}$  (31).

### Curry leaf

A monitoring study of curry leaves was conducted in Kerala and reported residues of 12 pesticides, including chlorpyrifos, quinalphos, profenofos, triazophos, methyl parathion, cypermethrin,  $\alpha$ -endosulfan, malathion, fenpropathrin, cyfluthrin, bifenthrin and ethion, at varying concentrations (32). Curry leaf samples gathered from various markets across Kerala revealed a wide range of pesticide residues in curry leaf, including profenophos, chlorpyrifos, bifenthrin, cypermethrin, ethion, lambda cyhalothrin, fenpropathrin, methyl parathion, dimethoate, cyfluthrin, quinalphos, tricyclazole, tebuconazole, carbendazim, acetamiprid, clothianidin, hexaconazole, thiamethoxam, imidacloprid, trifloxystrobin, azoxystrobin, acephate, phenthoate, pyraclostrobin, monocrotophos and spirotetramat (26). 22 pesticides were reported

in curry leaf samples, with profenophos showing the highest residue level (25.69 mg kg<sup>-1</sup>) followed by  $\beta$ -cyfluthrin (12.65 mg kg<sup>-1</sup>), monocrotophos (12.23 mg kg<sup>-1</sup>), cypermethrin (10.81 mg kg<sup>-1</sup>), dimethoate (4.90 mg kg<sup>-1</sup>), ethion (4.79 mg kg<sup>-1</sup>), bifenthrin (2.87 mg kg<sup>-1</sup>) and chlorpyrifos (1.86 mg kg<sup>-1</sup>). At the same time, allethrin exhibited the lowest concentration (0.046 mg kg<sup>-1</sup>) (33). In a survey of 85 farm-gate samples, thiamethoxam residues were detected in 25 samples, with concentrations ranging from 0.03 to 0.49 mg kg<sup>-1</sup>. In contrast, chlorantraniliprole was detected in a single sample at 0.18 mg kg<sup>-1</sup> (34). Twenty-one pesticides were detected in curry leaf across 16 samples, with profenofos being the most frequently identified, followed by tolfenpyrad, thiamethoxam, bifenthrin, carbendazim, imidacloprid and pyriproxyfen (35).

### Celery

Malathion and profenofos residues in celery exceeded MRLs in samples collected from Egypt (15). Lambda-cyhalothrin (0.111 mg kg<sup>-1</sup>) and cypermethrin (0.028 mg kg<sup>-1</sup>) residues were detected in celery samples from China (20). A total of 25 pesticide residues were detected in 175 celery samples from China, among which carbofuran exceeded the MRL (36). Similarly, 35 pesticide residues were detected in 210 celery samples from Zhejiang Province, China, of which chlorothalonil, difenoconazole, isofenphos-methyl, avermectin and pendimethalin exceeded the MRL (37).

### Rocket

Residues of several pesticides were detected in rocket samples from Saudi Arabia, including lindane (0.005 mg kg<sup>-1</sup>), chlordane (0.009 mg kg<sup>-1</sup>), endosulfan (0.014 mg kg<sup>-1</sup>), chlorpyrifos (0.006 mg kg<sup>-1</sup>), cyfluthrin (0.86 mg kg<sup>-1</sup>), allethrin (0.008 mg kg<sup>-1</sup>), resmethrin (0.005 mg kg<sup>-1</sup>), fenvalerate (0.077 mg kg<sup>-1</sup>) and cypermethrin (0.166 mg kg<sup>-1</sup>), indicating widespread contamination by various insecticidal compounds (17). Residues of chlorpyrifos (0.123 mg kg<sup>-1</sup>) and resmethrin (0.1 mg kg<sup>-1</sup>) were also reported in rocket samples from Saudi Arabia (1). A total of 23 pesticide residues, including 12 insecticides, 9 fungicides, 1 herbicide and 1 acaricide, were detected in rocket samples from Turkey. Of these residues, 15 are approved by the EU, whereas 8 are not. Oxadiazine exhibited the highest mean concentration (1.615 mg kg<sup>-1</sup>), followed by carbamates (0.55 mg kg<sup>-1</sup>), neonicotinoids (0.472 mg kg<sup>-1</sup>) and pyrethroids (0.374 mg kg<sup>-1</sup>), indicating the presence of multiple pesticide classes in the samples (2).

### Parsley

The presence of lindane (0.006 mg kg<sup>-1</sup>), endosulfan (0.02 mg kg<sup>-1</sup>), ethoprophos (0.013 mg kg<sup>-1</sup>), diazinon (0.1 mg kg<sup>-1</sup>), permethrin (0.01 mg kg<sup>-1</sup>), cyfluthrin (0.007 mg kg<sup>-1</sup>), cypermethrin (0.014 mg kg<sup>-1</sup>), resmethrin (0.033 mg kg<sup>-1</sup>), amitraz (0.002 mg kg<sup>-1</sup>), mevinphos (0.006 mg kg<sup>-1</sup>) and thiobencarb (0.009 mg kg<sup>-1</sup>) was reported in parsley from Saudi Arabia, indicating contamination by various insecticidal and acaricidal compounds (17). Permethrin and cypermethrin residues were also reported in parsley from Saudi Arabia, with concentrations reaching 0.126 mg kg<sup>-1</sup> (1). Residues of 14 different pesticides were detected in 23 parsley samples from Turkey, including acetamiprid, chlorpyrifos-methyl, cypermethrin, ethoprophos, fluopyram, hexaconazole, imidacloprid, indoxacarb, malathion, methiocarb, pendimethalin, pymetrozine, pyrimethanil and tebuconazole, indicating significant pesticide contamination in the analysed samples (2). Parsley samples collected from different markets in Kerala contained residues of fenvalerate, quinalphos, hexaconazole, thiometon, chlorpyrifos, lambda-cyhalothrin and tebuconazole (26). These findings indicate the widespread

occurrence of multiple pesticide residues in parsley.

### Dissipation of pesticides in leafy vegetables

The dissipation behaviour of pesticides in leafy vegetables has been extensively studied and most studies confirm that residue decline follows first- or pseudo-first-order kinetics. The half-lives of these pesticides vary depending on the compound, environmental conditions and cultivation system.

#### Amaranthus and spinach

A controlled field experiment was conducted in China by spiking amaranthus and other leafy vegetables with pesticides such as metalaxyl, fluzifop-P-butyl, chlorpyrifos and lambda-cyhalothrin at 0.01–0.10 mg kg<sup>-1</sup>. Dissipation followed first-order kinetics with half-lives of 1.11–3.79 days for metalaxyl, 1.11–2.27 days for fluzifop-P-butyl, 1.13–5.17 days for chlorpyrifos and 1.77–6.24 days for lambda-cyhalothrin. Among the tested crops, spinach and amaranth retained higher residue levels than others (38). A field experiment was conducted in Vietnam to evaluate the dissipation dynamics of cypermethrin, emamectin benzoate and indoxacarb in *Amaranthus tricolor* L. Pesticides were applied 20 days after transplanting in both open-field and net-house conditions. Residue monitoring showed that cypermethrin had half-lives ranging from 3.0 to 5.3 days, emamectin benzoate from 0.37 to 0.64 days and indoxacarb from 12.5 to 13.5 hr. Dissipation was faster in open-field conditions compared to net-houses. Based on Codex MRLs, the safe harvest intervals were calculated as 7.70 days for cypermethrin and 1.40 days for emamectin benzoate under open-field conditions, whereas under net-house conditions, they were 9.40 and 1.80 days, respectively. For indoxacarb, safe harvesting could be carried out as early as 12 hr after application (39). The dissipation of imidacloprid in amaranth was studied in China and reported that its degradation followed a first-order kinetic model. The half-life of imidacloprid ranged from 0.29 days in open-field conditions to 1.29 days in greenhouse conditions. Residue levels declined to toxicologically safe limits within 7–14 days after application at dosages of 45 and 67.5 g a.i./ha under open-field and greenhouse conditions respectively, with average residues of 0.19 and 0.38 mg kg<sup>-1</sup> (40).

In Myanmar, the dissipation of dimethoate and diazinon were investigated in spinach. Residues of dimethoate declined from 1.3310 mg kg<sup>-1</sup> to 0.0157 mg kg<sup>-1</sup> over 216 hr (9 days), while diazinon declined from 0.8134 mg kg<sup>-1</sup> to 0.0104 mg kg<sup>-1</sup> over 168 hr (7 days). Complete degradation of dimethoate was observed at 264 hr (11 days) and of diazinon at 216 hr (9 days). The pre-harvest interval (PHI) for both insecticides was estimated to be 24 hr (41). In spinach, the dissipation of profenofos, imidacloprid and deltamethrin were investigated in Indonesia at different spray intervals before harvest. With a spray interval of 3 dph pre-harvest, profenofos residues were 6.07 times below the MRL, while at 7 dph, residues declined to 35.71 times below the MRL. For imidacloprid, residues were 1.87 times below the MRL at 3 dph and 5.30 times below at 7 dph. Deltamethrin residues at 3 dph were 1.01 times lower than the MRL and 5.1 times lower at 7 dph. This demonstrated that longer intervals before harvest significantly reduced residue levels, even though all values were within acceptable limits (31). Previous researchers studied dissipation in which imidacloprid, quinalphos and thiamethoxam were applied to spinach at single (25 g ai ha<sup>-1</sup>) and double (50 g ai ha<sup>-1</sup>) doses. Imidacloprid residues persisted for up to 7 days, with half-lives of 1.5 and 2.5 days and pre-harvest intervals of 6.5 and 7.5 days for the respective doses. Quinalphos residues were detectable up to the 10<sup>th</sup> and 15<sup>th</sup> day, showing a half-life of 1.5 days and a pre-harvest interval

of 8.5 days across both application rates. Thiamethoxam residues persisted up to the 7<sup>th</sup> and 10<sup>th</sup> days, with half-lives of 2.0 days and pre-harvest intervals of 10.5 and 11 days for the single and double doses, respectively (42).

In India, the dissipation of dimethoate was studied in foxtail amaranthus and spinach under field conditions at Coimbatore, Tamil Nadu. Dimethoate was applied twice at 10-day intervals at 200 and 400 g ai ha<sup>-1</sup>. Initial deposits were 7.25 µg g<sup>-1</sup> and 19.51 µg g<sup>-1</sup> in foxtail amaranthus and 18.37 µg g<sup>-1</sup> and 29.46 µg g<sup>-1</sup> in spinach, for the two doses, respectively. Residues declined below detectable levels (< 0.05 µg g<sup>-1</sup>) by 10 days after treatment in foxtail amaranthus and by 15–20 days in spinach. The half-lives of dimethoate were 0.85 and 0.86 days in foxtail amaranthus and 2.22 and 1.12 days in spinach at 200 and 400 g ai ha<sup>-1</sup>, respectively (43).

### Cabbage

Several studies have documented the dissipation behaviour of various insecticides in cabbage. Imidacloprid residues declined from 0.24 mg kg<sup>-1</sup> to below detectable levels (BDL) within five days, with a half-life of 1.70 days (44). Dissipation of spinosad applied at 17.50 and 35 g ai ha<sup>-1</sup> was reported, with residues decreasing from 2.97 and 5.85 mg kg<sup>-1</sup> to BDL in 10 and 15 days, respectively (45). The dissipation of multiple insecticides, namely chlorpyrifos, cyhalothrin, cypermethrin, deltamethrin, dimethoate and fenvalerate, was assessed, with residues declining from initial levels of 1.83, 0.27, 0.37, 0.10, 3.90 and 1.36 mg kg<sup>-1</sup> to BDL within 10, 6, 8, 2, 10 and 12 days, respectively. The corresponding half-lives were 2.0, 1.60, 2.30, 1.50, 1.60 and 2.20 days (46). Chlorfenapyr dissipated from 1.90 mg kg<sup>-1</sup> to BDL within 10 days, with a half-life of 3.62 days (47). Flubendiamide residues in cabbage declined from 0.49 mg kg<sup>-1</sup> to BDL over a period of 15 days (48). Quinalphos residues dissipated from 0.75 mg kg<sup>-1</sup> to BDL within 10 days, exhibiting a half-life of 2.70 days (49).

The quinalphos dissipation in cabbage was documented under plain and hill conditions, observing reductions from 0.24 and 2.66 mg kg<sup>-1</sup> to BDL within 5 and 7 days, respectively (50). The chlorpyrifos and profenophos were reported dissipated from 1.52 and 1.02 mg kg<sup>-1</sup> to BDL within 15 days, with half-lives of 1.91 and 2.01 days respectively (51). Further, in earlier studies, compared insecticide persistence in cabbage grown on the plains and in the hills. In plain regions, flubendiamide showed the highest persistence (20 days), followed by acetamiprid and quinalphos (10 days each), whereas in hill regions, flubendiamide, cypermethrin and quinalphos persisted for up to 10 days. The shortest persistence was recorded for fipronil (3 days) in plains and acetamiprid (3 days) in hills (52).

Cabbage was treated with a co-formulation of novaluron and lambda-cyhalothrin at the recommended (750 g ai ha<sup>-1</sup> each) and double (1500 g ai ha<sup>-1</sup> each) doses. The half-lives of novaluron ranged from 1.77–2.51 days at the recommended dose and 2.00–3.38 days at the double dose, while those of lambda-cyhalothrin ranged from 1.36–2.24 days and 1.69–3.82 days, respectively (53). The dissipation of imidacloprid, difenoconazole and chlorothalonil in cabbage followed first-order kinetics, with half-lives of 1.35, 2.28 and 2.47 days, respectively (54). Dissipation of ethion in cabbage was evaluated following two foliar applications at recommended and double doses (500 and 1000 g ai ha<sup>-1</sup>). Residues declined with half-lives of 3.11 and 2.52 days, respectively and fell below the quantification limit by the 7<sup>th</sup> day at the recommended dose, indicating minimal residue risk (55).

The dissipation of deltamethrin, chlorantraniliprole and fipronil,

applied at recommended doses of 12.5, 30 and 50 g ai ha<sup>-1</sup> respectively, was studied in cabbage. Fipronil was the most persistent, detectable up to the 7<sup>th</sup> day at 0.01 mg kg<sup>-1</sup>, while chlorantraniliprole and deltamethrin residues declined to 0.11 mg kg<sup>-1</sup> and 0.03 mg kg<sup>-1</sup> by the 5<sup>th</sup> day. The half-lives were estimated as 1.81 days for chlorantraniliprole, 1.07 days for fipronil and 1.42 days for deltamethrin (56). Cydalaniliprole exhibited rapid dissipation in cabbage with a half-life of 1.8–2.7 days (57). In cabbage, initial afidopyropen residues ranged from 8.75 to 24.53 mg kg<sup>-1</sup> across treatments of 7.5, 9.75 and 12 g ai ha<sup>-1</sup>. Over 90 % of the residues dissipated within the first 10 days post-application. The corresponding half-lives were 1.45, 2.45 and 2.01 days for the respective doses (58).

The persistence of imidacloprid, lambda-cyhalothrin and spiromesifen on cabbage was evaluated at single doses of 25, 15 and 96 g ai ha<sup>-1</sup> and double doses of 50, 30 and 192 g ai ha<sup>-1</sup> respectively. Initial residues for the single and double doses were 0.39–0.80 mg kg<sup>-1</sup> for imidacloprid, 0.20–0.41 mg kg<sup>-1</sup> for lambda-cyhalothrin and 0.74–1.58 mg kg<sup>-1</sup> for spiromesifen. Spiromesifen was the most persistent (10 days for both doses), followed by lambda-cyhalothrin (7 and 10 days) and imidacloprid (5 and 7 days). The safe waiting periods were 5, 6 and 9 days for single doses and 6, 7 and 11 days for double doses, with half-lives of 1.6 days (imidacloprid), 2.5–3.1 days (lambda-cyhalothrin) and 1.8–1.9 days (spiromesifen) (59). Field trials showed that flonicamid dissipation in cabbage followed first-order kinetics, with a half-life of 2.2 days (60). In cabbage, initial residues of azoxystrobin, thiamethoxam and carbendazim at the recommended doses were 6.06, 2.17 and 36.55 mg kg<sup>-1</sup>, with half-lives of 26.65, 18.24 and 33.00 days respectively. At double the recommended doses, the initial concentrations increased to 16.77, 7.70 and 129.97 mg kg<sup>-1</sup>, with half-lives of 15.40, 11.55 and 17.77 days, respectively (61). Spiromesifen, when applied at 125 g ai ha<sup>-1</sup>, showed an initial residue of 0.343 mg kg<sup>-1</sup> and a half-life of 3.79 days in cabbage (62).

### Curry leaf

The chlorpyrifos residues in curry leaf showed initial deposits of 12.60 and 26.14 µg g<sup>-1</sup> at the recommended and double doses, respectively. Over 80 % of the residues dissipated within three days for both treatments, reaching below the detection limit by the 30<sup>th</sup> and 35<sup>th</sup> day. The corresponding half-lives were 4.15 and 4.40 days (63). Field evaluations were done on curry leaf to assess the dissipation behaviour of carbendazim (500 g ai ha<sup>-1</sup>) and cypermethrin (50 g ai ha<sup>-1</sup>). Initial residue levels were 16.00 mg kg<sup>-1</sup> for carbendazim and 13.09 mg kg<sup>-1</sup> for cypermethrin, which declined to 0.04 mg kg<sup>-1</sup> and 0.28 mg kg<sup>-1</sup> respectively. Residues fell below the detection level by 20 days for carbendazim and 10 days for cypermethrin (64). In a supervised field trial on curry leaf, dimethoate applied twice at 200 and 400 g ai ha<sup>-1</sup> resulted in initial residues of 5.75 and 10.38 mg kg<sup>-1</sup> respectively. More than 99.98 % dissipation occurred by 30 days after the application. The calculated half-lives were 3.25 and 3.64 days, with safe waiting periods of 34.77 and 42.00 days for the recommended and double doses respectively (65). A dissipation study was conducted in which dimethoate applied at 200 and 400 g ai ha<sup>-1</sup> showed initial residues of 5.20 and 10.05 µg g<sup>-1</sup> for dimethoate and 0.33 and 0.48 µg g<sup>-1</sup> for o-methoate. Their corresponding half-lives were 3.07 and 3.34 days (66). In curry leaf, chlorantraniliprole residues declined below the quantification limit within 30–40 days and thiamethoxam within 35–40 days. Both insecticides followed first-order dissipation, with half-lives of 5.08–5.28 days for chlorantraniliprole and 3.50–3.96 days for thiamethoxam at single and double doses respectively (34).

## Lettuce

A study conducted in China evaluated the dissipation of pyrethrins in leaf lettuce under both open-field and greenhouse conditions. The initial residue levels were higher under greenhouse conditions ( $0.57 \text{ mg kg}^{-1}$ ) compared to open-field cultivation ( $0.25 \text{ mg kg}^{-1}$ ). Furthermore, pyrethrins dissipated more rapidly in field-grown lettuce, with a shorter half-life (0.7 days) than that observed under greenhouse conditions (1.1 days) (67). In another study conducted in China, chlorpyrifos dissipation in lettuce under greenhouse conditions showed an initial deposition of  $25.3 \pm 2.0 \text{ mg kg}^{-1}$ . The residues declined progressively over time and reached  $0.56 \pm 0.06 \text{ mg kg}^{-1}$  at a pre-harvest interval of 21 days, with a reported half-life of 3.92 days (68).

## Management of pesticide residues in leafy vegetables

Pesticides, though indispensable for crop protection, leave residues that may pose serious health risks when vegetables are consumed without adequate decontamination. Since leafy vegetables cannot be peeled and possess a large surface area prone to pesticide deposition, effective removal strategies are essential. Several physical, chemical and household methods have been investigated for their efficacy in reducing residues. Tap water washing is the most common method used in households; however, its effectiveness is often limited because many pesticides are hydrophobic (69). Cooking methods, including blanching, boiling, stir-frying and drying, have shown varied effects on residue removal.

## Cabbage

Washing followed by boiling cabbage for 20 min removed 80–90 % of diazinon and dichlorvos residues (70). Washing cabbage with a 2 % NaCl solution for 5 min removed chlorpyrifos (15.96 %) and cypermethrin (10.68 %) and further demonstrated that stir-frying for 5 min markedly reduced residues of chlorpyrifos (86.60 %), cypermethrin (84.70 %) and chlorothalonil (84.80 %) (46). Substantial reductions in quinalphos residues in cabbage, with washing under running tap water eliminating 69.02–77.68 %, while cooking achieved a 41.30–45.20 % reduction (71). Cooking decreased chlorpyrifos residues by 18.30 % in cabbage, whereas tap-water washing removed 17–40 % of chlorantraniliprole from cabbage (72, 14). Further, Padmanabhan reported that cooking cabbage for 15 min was the most effective in reducing quinalphos residues (54.79 %) under plain conditions and cypermethrin residues (66.47 %) under hill conditions (52). Chinese cabbage was investigated and reported that washing under running water for 10 min and soaking in diluted vinegar solution for 10 min were the most effective methods for removing 2,4-D and atrazine residues (73).

## Curry leaf

Dipping curry leaves in a 2 % tamarind solution for 15 min, followed by washing, removed 70–88 % of methyl parathion, malathion, chlorpyrifos, quinalphos, profenofos, ethion, cypermethrin and fenvalerate residues (32). Dipping curry leaves in water for 15 min removed malathion (25.88 %), chlorpyrifos (10.80 %), quinalphos (18.59 %), profenofos (21.66 %) and cypermethrin (8.19 %) (74). Curry leaves and found that dimethoate was effectively removed by cooking (93.33 %), sodium bicarbonate (48.07 %) and tamarind water (42.15 %). Quinalphos removal was most effective through drying (73.97 %) and cooking (64.79 %), followed by sodium bicarbonate (55.60 %) and tamarind water (38.96 %). Acephate residues were reduced by 80.91 % through cooking, 58.74 % by

tamarind water, 52.84 % by acetic acid and 45.04 % by tap water washing. Imidacloprid was removed by 79.89 % through cooking and 49.42 % with tamarind water. For bifenthrin, tamarind water (46.97 %) and cooking (42.54 %) were the most effective (75). Exposure of curry leaves to 2 % salt solution for 15 min, followed by 15 min of boiling, resulted in a substantial reduction of pesticide residues, with a removal efficiency of 98.47 % (62) (Table 2). Paramasivam evaluated various household decontamination techniques for reducing pesticide residues in curry leaves and found that 2 % lemon juice solution was the most effective (35.71–56.52 %), followed by 2 % tamarind solution (23.48–42.94 %), hot water treatment (18.44–46.74 %) and 2 % salt solution (10.98–42.71 %), while tap water exhibited the lowest reduction (3.57–27.84 %) (Table 3) (76).

## Spinach

Washing spinach removed 22.2 % of endosulfan (77). Previous researchers studied spinach and tested acidic (acetic acid, citric acid), alkaline (sodium chloride, sodium carbonate) and biological (radish, ginger, garlic, lemon extracts) solutions. Average reductions ranged from 10.21–79.68 % for deltamethrin, 22.60–89.99 % for cypermethrin, 22.95–94.21 % for chlorpyrifos and 11.24–70.32 % for endosulfan. Among the treatments, 10 % acetic acid achieved the highest reductions: 79.68 % for deltamethrin, 89.99 % for cypermethrin, 94.21 % for chlorpyrifos and 70.32 % for endosulfan. Sodium carbonate (10 %) showed a maximum reduction of 73.51 % in alkaline treatments (78). Early results reported that washing removed only 0–48 % of deltamethrin, iprodione, mancozeb and propamocarb, while blanching at 88 °C for 5 min achieved reductions of up to 72 % in spinach. Imidacloprid and thiamethoxam residues were also removed more efficiently by boiling and blanching than by washing, likely due to pesticide hydrolysis at higher temperatures. Their solubility and polarity also contributed to their higher removal rates (69). Among the decontamination techniques assessed, hot-water cooking for 10 min was the most effective, removing imidacloprid, thiamethoxam and quinalphos residues from spinach by 99.52 %, 93.21 % and 33.45 % respectively. Dipping in 2 % salt solution for 10 min was the next most effective method, eliminating 77.74 %, 68.21 % and 27.80 % of these residues (Fig. 1). A similar 2 % salt-solution dip for 10 min was also found to reduce imidacloprid, thiamethoxam and quinalphos residues by 75.18 %, 67.31 % and 18.60 % respectively (42).

## Amaranthus

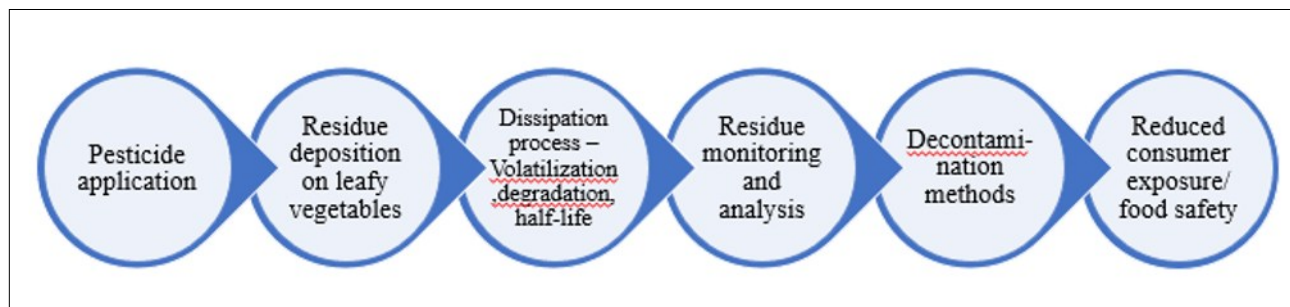
The efficacy of veggie wash ( $10 \text{ mL L}^{-1}$  for 10 min) for decontaminating amaranthus, with notable reductions in chlorpyrifos (61.20 %), cypermethrin (75.40 %), profenofos (78.50 %), quinalphos (73.70 %), fenvalerate (76.40 %), ethion (77.90 %), lambda-cyhalothrin (76.90 %), dimethoate (85.60 %) and bifenthrin (68.30 %) (79). Previous researchers evaluated decontamination methods for organophosphate residues in amaranth sprayed with chlorpyrifos, dimethoate, ethion, malathion, profenofos and quinalphos. Dipping in 1 % veggie wash for 20 min, followed by three rinses and cooking, was the most effective, reducing residues by 83 %. Other effective treatments included 1 % veggie wash for 20 min (78 %), veggie wash for 10 min plus cooking (76 %) and 2 % vinegar (74 %) (80). For synthetic pyrethroid residues in amaranth, early reports reported that dipping in a 2 % tamarind solution, 1 % veggie wash for 10 min, followed by three rinses and cooking and 2 % salt were most effective, reducing residues by 67 %, 64 % and 63 % respectively (81).

**Table 2.** Summary of pesticide half-lives in leafy vegetables

| Crop       | Pesticide           | Half-life (days) | Reference |
|------------|---------------------|------------------|-----------|
| Amaranthus | Metalaxyl           | 1.11–3.79        | 38        |
|            | Fluazifop-p-butyl   | 1.11–2.27        |           |
|            | Chlorpyrifos        | 1.13–5.17        |           |
|            | Lambda-cyhalothrin  | 1.77–6.24        |           |
|            | Cypermethrin        | 3.0–5.3          | 39        |
|            | Emamectin benzoate  | 0.37–0.64        |           |
|            | Indoxacarb          | 12.5–13.5 hr     | 40        |
|            | Imidacloprid        | 0.29–1.29        |           |
| Spinach    | Dimethoate          | 0.85–0.86        | 43        |
|            | Imidacloprid        | 1.5–2.5          | 42        |
|            | Quinalphos          | 1.5              |           |
|            | Thiamethoxam        | 2.0              | 43        |
|            | Dimethoate          | 1.12–2.22        |           |
|            | Imidacloprid        | 1.70             | 44        |
|            | Chlorpyrifos        | 2                | 46        |
|            | Cyhalothrin         | 1.60             |           |
|            | Cypermethrin        | 2.30             |           |
|            | Deltamethrin        | 1.50             |           |
|            | Dimethoate          | 1.60             | 47        |
|            | Fenvalerate         | 2.20             |           |
|            | Chlorfenapyr        | 3.62             | 49        |
|            | Quinalphos          | 2.70             | 51        |
|            | Chlorpyrifos        | 1.91             |           |
|            | Profenophos         | 2.01             | 53        |
| Cabbage    | Novaluron           | 1.77–3.38        |           |
|            | Lambda-cyhalothrin  | 1.36–3.82        | 54        |
|            | Imidacloprid        | 1.35             |           |
|            | Difenoconazole      | 2.28             | 55        |
|            | Chlorothalonil      | 2.47             |           |
|            | Ethion              | 2.52–3.11        | 56        |
|            | Deltamethrin        | 1.42             |           |
|            | Chlorantraniliprole | 1.81             | 57        |
|            | Fipronil            | 1.07             |           |
|            | Cyclaniliprole      | 1.8–2.7          | 58        |
|            | Afidopyropen        | 1.45–2.45        |           |
|            | Imidacloprid        | 1.6              | 59        |
|            | Lambda-cyhalothrin  | 2.5–3.1          |           |
|            | Spiromesifen        | 1.8–1.9          | 60        |
|            | Flonicamid          | 2.2              |           |
|            | Azoxystrobin        | 15.40            | 61        |
|            | Thiamethoxam        | 11.55            |           |
|            | Carbendazim         | 17.77            | 62        |
|            | Spiromesifen        | 3.79             |           |
| Curry leaf | Chlorpyrifos        | 4.15–4.40        | 63        |
|            | Dimethoate          | 3.25–3.64        | 65        |
|            | Dimethoate          | 3.07–3.34        | 68        |
|            | Chlorantraniliprole | 5.08–5.28        | 34        |
|            | Thiamethoxam        | 3.50–3.96        |           |
| Lettuce    | Pyrethrin           | 0.7–1.1          | 67        |
|            | Chlorpyrifos        | 3.92             | 68        |

**Table 3.** Comparative reduction of pesticide residues through different decontamination methods in leafy vegetables

| Crop       | Decontamination approach                                         | Pesticide               | Reduction (%) | Reference |
|------------|------------------------------------------------------------------|-------------------------|---------------|-----------|
| Cabbage    | Washing followed by boiling for 20 min                           | Diazinon and dichlorvos | 80–90         | 70        |
|            | Washing with 2 % NaCl solution for 5 min                         | Chlorpyrifos            | 15.96         | 46        |
|            |                                                                  | Cypermethrin            | 10.68         |           |
|            |                                                                  | Chlorpyrifos            | 86.60         |           |
|            | Stir-frying for 5 min                                            | Cypermethrin            | 84.70         |           |
|            |                                                                  | Chlorothalonil          | 84.80         | 71        |
|            | Washing under running tap water                                  | Quinalphos              | 69.02–77.68   |           |
|            | Cooking                                                          |                         | 41.30–45.20   |           |
|            | Cooking                                                          | Chlorpyrifos            | 18.30         | 72        |
|            | Washing under tap water                                          | Chlorantraniliprole     | 17–40         | 14        |
|            | Cooking for 15 min                                               | Quinalphos              | 54.79         | 52        |
|            |                                                                  | Cypermethrin            | 66.47         |           |
|            |                                                                  | Malathion               | 25.88         |           |
| Curry leaf | Dipping in water for 15 min                                      | Chlorpyrifos            | 10.80         | 74        |
|            |                                                                  | Quinalphos              | 18.59         |           |
|            |                                                                  | Profenofos              | 21.66         |           |
|            |                                                                  | Cypermethrin            | 8.19          |           |
|            | Cooking                                                          |                         | 93.33         | 75        |
|            | Sodium bicarbonate                                               | Dimethoate              | 48.07         |           |
|            | Tamarind water                                                   |                         | 42.15         |           |
|            | Drying                                                           |                         | 73.97         |           |
|            | Cooking                                                          |                         | 64.79         |           |
|            | Sodium bicarbonate                                               | Quinalphos              | 55.60         |           |
|            | Tamarind water                                                   |                         | 38.96         |           |
|            | Cooking                                                          |                         | 80.91         |           |
|            | Tamarind water                                                   |                         | 58.74         |           |
|            | Acetic acid                                                      | Acephate                | 52.84         |           |
|            | Tap water washing                                                |                         | 45.04         |           |
|            | Cooking                                                          |                         | 79.89         |           |
|            | Tamarind water                                                   | Imidacloprid            | 49.42         |           |
|            | Tamarind water                                                   |                         | 46.97         |           |
|            | Cooking                                                          | Bifenthrin              | 42.54         |           |
| Spinach    | Washing with water                                               | Endosulfan              | 22.2          | 77        |
|            |                                                                  | Deltamethrin            | 79.68         |           |
|            |                                                                  | Cypermethrin            | 89.99         |           |
|            | 10 % acetic acid                                                 | Chlorpyrifos            | 94.21         | 78        |
|            |                                                                  | Endosulfan              | 70.32         |           |
|            |                                                                  | Imidacloprid            | 99.52         |           |
|            | Hot-water cooking for 10 min                                     | Thiamethoxam            | 93.21         | 42        |
|            |                                                                  | Quinalphos              | 33.45         |           |
|            |                                                                  | Imidacloprid            | 77.74         |           |
|            | Dipping in 2 % salt solution for 10 min                          | Thiamethoxam            | 68.21         | 79        |
|            |                                                                  | Quinalphos              | 27.80         |           |
|            |                                                                  | chlorpyrifos            | 61.20         |           |
|            |                                                                  | Cypermethrin            | 75.40         |           |
|            |                                                                  | Profenophos             | 78.50         |           |
| Amaranthus | Veggie wash (10 mL L <sup>-1</sup> for 10 min)                   | Quinalphos              | 73.70         | 84        |
|            |                                                                  | Fenvalerate             | 76.40         |           |
|            |                                                                  | Ethion                  | 77.90         |           |
|            |                                                                  | Lambda-cyhalothrin      | 76.90         | 84        |
|            |                                                                  | Dimethoate              | 85.60         |           |
|            |                                                                  | Bifenthrin              | 68.30         |           |
|            | 2 % tamarind solution                                            |                         | 67            | 84        |
|            | 1 % veggie wash for 10 min, followed by three rinses and cooking | Synthetic pyrethroids   | 64            |           |
|            | 2 % salt solution                                                |                         | 63            |           |
| Lettuce    | Grape vinegar with water                                         | Sulfoxaflor             | 98.08         | 82        |
|            | Grape vinegar containing 6 % acetic acid                         | Deltamethrin            | 66            |           |
|            |                                                                  | Fluopicolide            | 76.49         |           |
|            |                                                                  | Fluopyram               | 80.63         |           |
|            | Filtered rice water                                              | Pyrimethanil            | 74.42         |           |
|            |                                                                  | Pyraclostrobin          | 95.67         |           |
|            | Lemon juice                                                      | Boscalid                | 90.21         |           |
|            | Baking soda solution                                             | Sulfoxaflor             | 96.6          |           |
|            | Washing with cold water                                          | Fluopyram               | 78.5          |           |
|            |                                                                  | Pyraclostrobin          | 80.5          |           |
|            |                                                                  | Boscalid                | 77.4          |           |
|            |                                                                  | Sulfoxaflor             | 96.2          |           |
|            | Washing with hot water                                           | Fluopyram               | 78            |           |
|            |                                                                  | Pyraclostrobin          | 94.4          |           |
|            |                                                                  | Boscalid                | 78.4          |           |



**Fig. 1.** Schematic representation of the pathway from pesticide application to residue deposition, dissipation/monitoring and decontamination processes in leafy vegetables.

### Lettuce

Among the various household decontamination methods evaluated, grape vinegar diluted with water was highly effective in removing sulfoxaflor residues (98.08 %), while grape vinegar containing 6 % acetic acid showed considerable efficacy against deltamethrin residues (66 %). Filtered rice water effectively reduced residues of fluopicolide (76.49 %), fluopyram (80.63 %) and pyrimethanil (74.42 %). Lemon juice exhibited the highest removal efficiency for pyraclostrobin (95.67 %), whereas baking soda solution was particularly effective in reducing boscalid residues (90.21 %). In addition, cold and hot tap water also removed sulfoxaflor (96.6 %, 96.2 %), pyraclostrobin (80.5 %, 94.4 %), fluopyram (78.5 %, 78 %) and boscalid (77.4 %, 78.4 %) residues, indicating the potential of simple household washing practices in minimising pesticide residues (82). Furthermore, the addition of chlorine dioxide (CD) ( $20 \text{ mg L}^{-1}$ ) to tap water significantly enhanced the removal of phorate and diazinon residues from lettuce compared to washing with tap water alone. Studies conducted in aqueous solutions demonstrated that CD supplementation increased the removal efficiency of phorate and diazinon by approximately 40–80 % and 10–20 % respectively, suggesting its potential role in facilitating pesticide degradation and improving residue decontamination efficiency (83).

### Conclusion

Leafy vegetables, though highly nutritious and widely consumed, often contain pesticide residues that pose significant risks to consumer health. Evidence from monitoring studies across multiple countries highlights the alarming frequency with which residues exceed maximum residue limits. Among the detected pesticide residues, organophosphate insecticides most frequently exceeded the prescribed maximum residue limits (MRLs) across leafy vegetables, followed by organochlorine pesticides, pyrethroids and neonicotinoids, indicating widespread misuse or off label use. Organophosphates and synthetic pyrethroids generally exhibited rapid dissipation and shorter persistence in leafy vegetables. Neonicotinoids showed variable persistence depending on the crop and cultivation conditions, whereas newer insecticide molecules demonstrated moderate dissipation behaviour. In contrast, fungicides exhibited comparatively higher persistence than most insecticides, indicating their prolonged retention in leafy vegetable crops. Variations in pesticide dissipation rates, driven by factors such as chemical properties, crop characteristics, application practices and environmental conditions, underscore the importance of adhering to recommended pre-harvest intervals (PHIs) to ensure food safety.

Management strategies for pesticide residues in leafy vegetables have shown variable levels of effectiveness. Thermal processing methods such as cooking, boiling and stir-frying showed the highest pesticide reduction efficiencies in leafy vegetables compared to simple washing treatments. Washing with acidic and alkaline solutions, including vinegar, acetic acid, tamarind water, sodium bicarbonate, salt solution and commercial veggie wash formulations, was more effective than plain tap water washing. Organophosphate insecticides were generally removed more efficiently during processing, whereas pyrethroids and certain fungicides exhibited comparatively greater persistence. Overall, the efficiency of pesticide residue removal was strongly influenced by the chemical nature of the pesticide and the type of decontamination method employed. Despite the availability of studies on pesticide residue dissipation and decontamination in leafy vegetables, significant research gaps still remain. Limited information is available on residue dissipation patterns in lettuce, rocket and parsley under diverse agroclimatic conditions. Further studies are also required to validate the efficiency of decontamination methods against neonicotinoids and other newer pesticide classes, which are increasingly used in vegetable production.

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### Authors' contributions

SSMR the initial draft. AP critically reviewed the manuscript, contributed to structuring and interpretation of the literature. Both authors have read and approved the final manuscript.

### Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

### Declaration of AI-assisted technologies in the writing process

AI tools were used only for language editing and improving readability. All scientific contents were prepared solely by the authors.

## Literature search/Methods section

Crops were selected based on their global consumption significance and availability of published residue monitoring data.

Databases searched: Scopus, Google Scholar, Pubmed, Web of Science

Search terms: ('pesticide residues' OR 'pesticide contamination') AND ('leafy vegetables' OR 'cabbage' OR 'spinach' OR 'amaranthus' OR 'celery' OR 'rocket' OR 'parsley' OR 'curry leaf' OR 'lettuce') AND ('monitoring' OR 'dissipation' OR 'decontamination' OR 'management' OR 'MRL').

Date range of the search: 2000–25

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