PLANT SCIENCE TODAY
Vol 12(4): 1-10
https://doi.org/10.14719/pst.10289

eISSN 2348-1900

RESEARCH ARTICLE

Influence of pre-harvest spray of cypermethrin on residual levels and quality of strawberry fruit

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Received: 26 June 2025; Accepted: 27 October 2025; Available online: Version 1.0: 13 November 2025; Version 2.0: 27 November 2025

Cite this article: Saswati E, Most ZI, Sanchita R, Nazrul IM, Mohammad DHP, Shormin C. Influence of pre-harvest spray of cypermethrin on residual levels and quality of strawberry fruit. Plant Science Today. 2025; 12(4): 1-10. https://doi.org/10.14719/pst.10289

Abstract

Pesticides increase agricultural production, but they also have negative impacts on human health when used in excess. Pesticide residues must be lower than the maximum residual limits (MRLs) for safe consumption. Field investigations were done in 2021 to assess the residues of the pyrethroid insecticide cypermethrin (Ripcord 10E) in ripe strawberry fruits. Following insecticide application, residue levels were assessed at different harvest intervals: 0 (2 hr), 1, 3, 5, 7, 10 and 12 days. According to the findings, after spraying (DAS), strawberry fruits had the highest residual levels (0.874 mg/kg). Up to 7 DAS, the observed residual level was higher (0.101 mg/kg) than maximum residue limits of European Union (EU-MRLs). On 10 DAS, the measured residue level decreased below the MRLs. As a result of our findings, Pre-Harvest Interval (PHI) of cypermethrin was detected for strawberries up to 10 DAS. The data showed that no pesticide residues were identified at 12 DAS. Insecticide spraying has an impact on strawberry quality as well. Fruits' phenolic content increased steadily between 1 and 7 DAS of cypermethrin. Pre-harvest cypermethrin spray can delay the increase of TSS and sustain TA content. Therefore, it can be said that the pesticide residues found were lower than the corresponding EU-MRLs, indicating that picked strawberries are safe for consumers.

Keywords: cypermethrin; pre-harvest interval; quality attributes; residual level; strawberry

Introduction

Strawberry is a delicious and nutritious fruit, renowned for its vibrant colour, fragrant aroma and sweet taste. Strawberries are an excellent source of vitamins and have a significant dietetic value (1). Strawberries are widely consumed around the world and contain key nutrients like vitamin C, folate and polyphenols (2). Long-term consumption of diets high in polyphenols may provide protection against the onset of several chronic diseases, including diabetes, cancer, cardiovascular diseases (CVDs), neurodegenerative diseases, inflammatory disorders and infectious diseases (3).

This fruit is highly valuable both for fresh consumption and in the processing industry. Although it is a promising crop, the high prevalence of insect pests contributes to its poor yield and quality. Pests and diseases drastically reduce strawberry fruit yield and quality, causing growers to suffer large financial losses (4). Farmers in our country experience significant strawberry yield losses each year because of severe insect pest infestations such as *Frankliniella occidentalis* Perg. (Thysanoptera, Thripidae), *Tetranychus urticae* Koch (Acari: Tetranychidae), *Phytonemus pallidus* Banks (Acari: Tarsonemidae), Verticillium sp., *Lygus* sp., *Pythium* sp., *Botrytis cinerea* Pers., *Phytophthora* spp., *Sphaerotheca pannosa* (Wallr.) Lév., *Rhizoctonia* sp. and *Fusarium* sp. during the growth period of crops and the post-harvest period (5). Pesticides play a crucial role in protecting crops and enhancing production by controlling insect pests and diseases (6). But their misuse and overuse cause severe health hazards and environmental degradation. For instance, careless and excessive use of these compounds can lead to groundwater and environmental contamination, while also disrupting the soil's microbial community (7). Pesticides cause significant harm to beneficial and non-target biota such as predators, honeybees, small animals, birds and plants (8). Blindness, liver ailments, elevated cholesterol, neurological toxicity, immunological and reproductive system abnormalities, prostate cancer, lymphomas, Parkinson's disease, multiple myeloma, genetic problems and infant mortality are some of the adverse health impacts (9).

The use of pesticides is constantly growing globally in response to the rising demand for food as the world's population continues to grow (10). The global increase in pesticide use can be attributed to several interconnected factors like rising global food demand, intensification of agricultural practices, pest resistance, economic pressure on farmers, lack of alternative, technological advances, increased awareness of pests and diseases and lack of effective regulations or enforcement. Together, these factors contribute to the growing use of pesticides worldwide, despite concerns about environmental and health impacts. More sustainable farming practices, along with stronger regulation and education, are needed to mitigate over-reliance on pesticides.

Pesticides increase agricultural production, but they also have negative impacts on human health when applied excessively (11). Assessment of the hazards of food exposure to 26 pesticides on strawberries revealed that, although the detection rates of these residues were significant, the acute and chronic exposure risks were below 100 % (12). Residues of pesticides must be below maximum residual limits (MRLs) for food to be safe to consume (13). Good Agricultural Practices (GAP) should be followed while using pesticides to ensure a safe food supply. Keeping an eye on pesticide residues is an essential part of GAP compliance. Pesticide residues in commercial produce must be monitored nationally using dependable multi-residue testing techniques.

Many industrialized nations determine the Maximum Residue Limits (MRLs) by the Potential Daily Intake (PDI) and Acceptable Daily Intake (ADI) levels. By limiting the amount of pesticide residues in food, these limits safeguard the health of consumers (14). In Bangladesh, however, monitoring systems and farmer awareness remain limited. Most strawberry growers are illiterate and unable to read or understand the information on pesticide labels. They often rely on pesticide dealers or retailers in their area, who lack proper knowledge about insects, pests, diseases and pesticides. These dealers typically recommend pesticides that pose serious risk to the environment and human health. It is considered normal practice to spray insecticides unusually and sell the fruits just 1-2 days after application (15). Since fruits are harvested and sold without regard for the pre-harvest interval, pesticide residue levels in strawberries and other fruits are likely to exceed the MRL. The issue of pesticide residue becomes even more serious because fruits are eaten raw.

Physiochemical indicators such total soluble solids (TSS), starch content and acid content were used to evaluate the quality of the fruits during harvest. Numerous biochemical alterations take place in plants when they are attacked by pathogens or exposed to physical, chemical, or biological stress. The expression of phenolic chemicals, which are crucial for plant resistance or susceptibility, may rise or fall because of these alterations (16). Phenolic compounds are an essential component of the plant's post-infection response. As a type of baseline resistance, they are found in healthy plant tissue, but their synthesis and accumulation tend to increase after infection.

Because pesticide use and crop output are closely related, it is important to monitor and thoroughly investigate any remaining pesticide residues, whether they persist in the environment. Pesticide residue detection and monitoring, especially in fruits and vegetables, are routinely carried out in many nations (17, 18). The most widely used insecticides in Bangladesh now are carbamates, pyrethroids and organophosphates (OP); organochlorine (OC) insecticides have been outlawed due to their persistence, toxicity and environmental bioaccumulation potential (19). Crop productivity may increase when these pesticides are employed, but there is a risk that the crops will get polluted by pesticide residue. It is critical to investigate the time following pesticide treatment in order to ensure a safe harvest. As a result, there is an urgent need to research the actual retention time of pesticides in fruits before environmental and health specialists take the required steps to draft laws, rules and regulations governing insecticide use in Bangladesh. Despite extensive international research on pesticide residues in strawberries, limited information is available on the degradation pattern of Cypermethrin and its potential effects on strawberry quality under the warm, humid subtropical conditions of Bangladesh.

Strawberry cultivation in Bangladesh is relatively new and expanding. However, farmers frequently apply pyrethroid insecticides during the late stages of fruit development, often just before harvest without recommended pre-harvest intervals. These local practices, coupled with climatic factors such as high temperature and humidity, may influence pesticide degradation rates and fruit quality differently compared to temperate regions.

Therefore, the present study aimed to determine the influence of a pre-harvest foliar spray of cypermethrin on the residual levels and quality attributes of strawberry fruits grown under the climatic conditions of Bangladesh.

This study was based on the hypothesis that pre-harvest Cypermethrin application would lead to detectable residues that decrease over time and may affect strawberry fruit quality.

Materials and Methods

Field experiment

A field experiment was performed at the experimental field of Horticulture Farm at Sher-e-Bangla Agricultural University (SAU), Dhaka, Bangladesh.

The experiment was laid out in a Randomized Complete Block Design (RCBD) with four replicates and treatments included: T_0 = Control (no pesticide), T_1 = Ripcord 10EC at recommended dose (1.5 mL L^{-1} water). Each block contained two plots (2 m × 2 m) randomly assigned to treatments, with a 0.5 m buffer between plots and 1 m between blocks to avoid spray drift. This synthetic pyrethroid pesticide is manufactured by BASF Bangladesh Limited and has batch number AP-335. After the strawberries were large enough to sell, a backpack sprayer was used to apply Ripcord 10EC in the field.

Chemicals

Sigma-Aldrich (St. Louis, MO, USA) provided the standard of cypermethrin (>99.6 % pure) through Bangladesh Scientific Pvt. ltd. in Dhaka, Bangladesh. Bangladesh Scientific Pvt. ltd., located in Dhaka, Bangladesh, supplied the gradient grade acetonitrile, analytical grade methanol, anhydrous magnesium sulphate ($MgSO_4$), sodium chloride (NaCl) and Primary Secondary Amine (PSA).

Sampling and sample preservation

For fruit sampling, 500 g of equally sized, ripe fruit were randomly collected from each replicate in the experimental field of the Horticulture farm at SAU at 0 (2 hr), 1, 3, 5, 7, 10 and 12 days after pesticide application. Samples were collected in clear, sealed plastic bags. Following appropriate labelling, all the samples were sent to the Bangladesh Agricultural Research Institute's (BARI) Entomology Division's Pesticide Analytical Laboratory in Gazipur.

Preparation of pesticide standard solution

Cypermethrin standard stock solutions were made in acetonitrile at a concentration of 1000 mg/L and stored at -20 °C until needed. The proper volume of each individual stock solution was added to a volumetric flask (50 mL), then acetonitrile was added to bring the flask to volume to create a standard solution of 50 mg/L in acetonitrile. The standard solution of 50 mg/L was converted into an intermediate standard solution of 10 mg/L in acetonitrile. After that, the required amount from the intermediate standard solution (10 mg/L) was transferred into seven other volumetric flasks of 10 mL to create working standard solutions of 0.1, 0.2, 0.5, 1.0, 2.0, 3.0 and 5.0 mg/L in acetonitrile. Before being used, all the standard solutions were stored at -20 °C in a freezer.

Extraction and clean up

Samples in this investigation were extracted and cleaned using the modified QuEChERS extraction procedure (6). In a polypropylene centrifuge tube of 50 mL, a representative 10 g fully homogenized portion of the sample was weighed. After that, the centrifuge tube was filled with 10 mL of acetonitrile (CH_3CN). After closing the centrifuge tube properly, it was agitated strongly for 30 sec with a vortex mixer. To prevent the formation of magnesium sulfate aggregates, anhydrous $MgSO_4$ (4 g) and NaCl (1 g) were then added to the centrifuge tube and it was agitated right away using a vortex mixer for a minute. The extract was then centrifuged at 5000 rpm for 5 min. A micro centrifuge tube 15 mL containing 120 mg Primary Secondary Amine (PSA) and 600 mg anhydrous $MgSO_4$ were filled with an aliquot of CH_3CN layer (3 mL). Next, it was centrifuged for 5 min at 4000 rpm after being well mixed by vertexing for 30 sec (Laboratory Centrifuges, Sigma-3K30, Germany). A 0.2 µm PTFE filter was used to filter 1 mL supernatant after centrifugation and it was transferred to a sterile GC vial for injection.

Instrumental analysis

Cypermethrin residues in sample extracts were found using a Shimadzu GC-2010 equipped with an Electron Capture Detector (ECD). Rtx-CLPesticides2 was the capillary column, measuring 30 m in length, 0.32 mm in ID and 0.25 µm in film thickness. Injection was done in split mode, with a split ratio of 10:0 and injector and detector temperatures of 280 °C and 300 °C, respectively. The temperature of the column was set to range from 160 °C for 1 min to 270 °C for 8 min at a rate of 10 °C /min . For GC-ECD, nitrogen served as both a make-up gas and a carrier. Peak retention periods in samples were compared to peaks in pure analytical standards to identify the suspected pesticide (Fig. 1).

Calibration curve preparation

Standard solutions containing varying concentrations of cypermethrin were produced and injected with appropriate instrument parameters prior to the injection of the sample extract. The four-pointed calibration curve of the reference solution of the relevant pesticide was used to calibrate the samples (retention duration, peak area, etc.). Standard fortified solutions of the relevant pesticide were used to continuously compute the linearity and determination coefficient at concentration levels ranging from 0.02 to 0.2 mg/kg, with an R^2value of 0.999 for the determination coefficient (Fig. 2). The GC program automatically expressed the sample data in mg/kg and each peak was identified by its retention duration.

Method validation

Validation of the method was done on parameters of precision, linearity, correlation coefficient (R^2), limit of detection (LOD) and limit of quantification (LOQ). The working range for the calibration of the Cypermethrin was 0.020 – 0.200 mg/kg where, the correlation coefficient (R^2) was 0.99. The limit of detection (LOD) and the limit of quantification (LOQ) were 0.048 and 0.146 mg/kg respectively. The average recovery percentage was 80-98 % with Relative Standard Deviation (RSD) for this calibration was 0.0000919 %, which indicates extremely high precision in the calibration data.

Determination of Pre-Harvest Interval (PHI)

Initially, the PHI was computed using the following methods to ascertain the amount of residues in each sample that was collected for the tested pesticide. First, the sampling day that came after MRL was chosen. Because the residue level was lower than MRL on that day, it was designated as PHI.

Quality attributes

Total soluble solids content

A digital refractometer (MA871; Romania) was used to measure the TSS content of strawberries. A dropper was used to collect strawberry juice and placed on the prism of the refractometer. The refractometer showed the total soluble solids (TSS) reading.

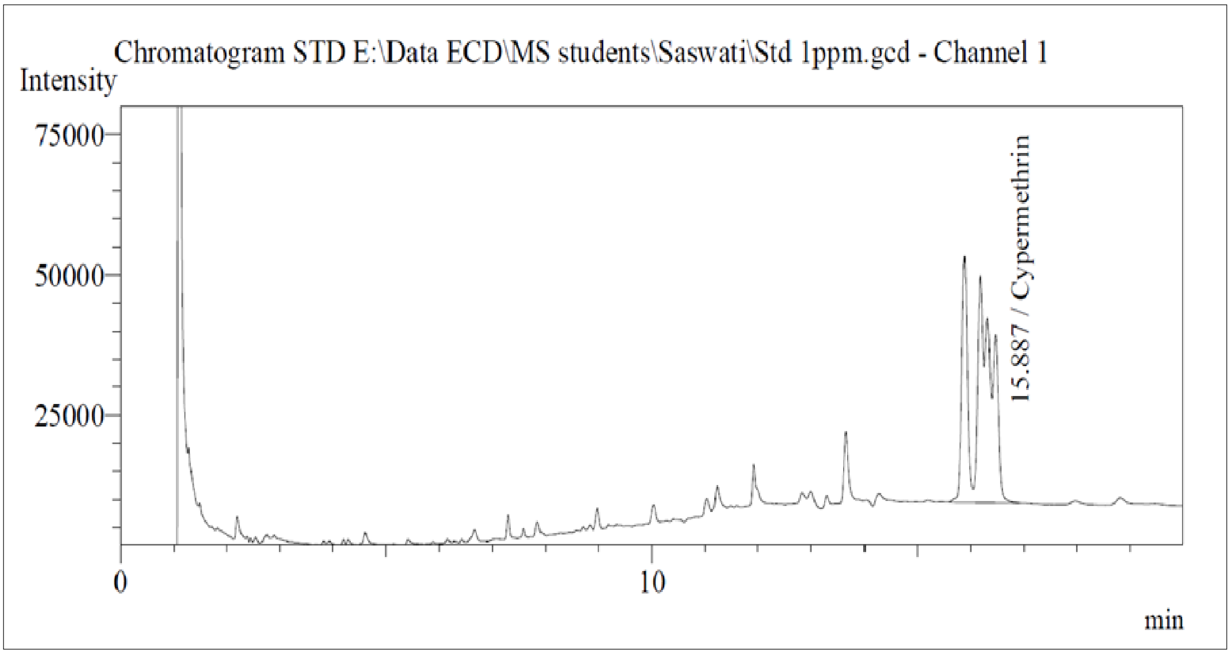

Fig. 1. Typical chromatogram of cypermethrin standard run by GC-ECD.

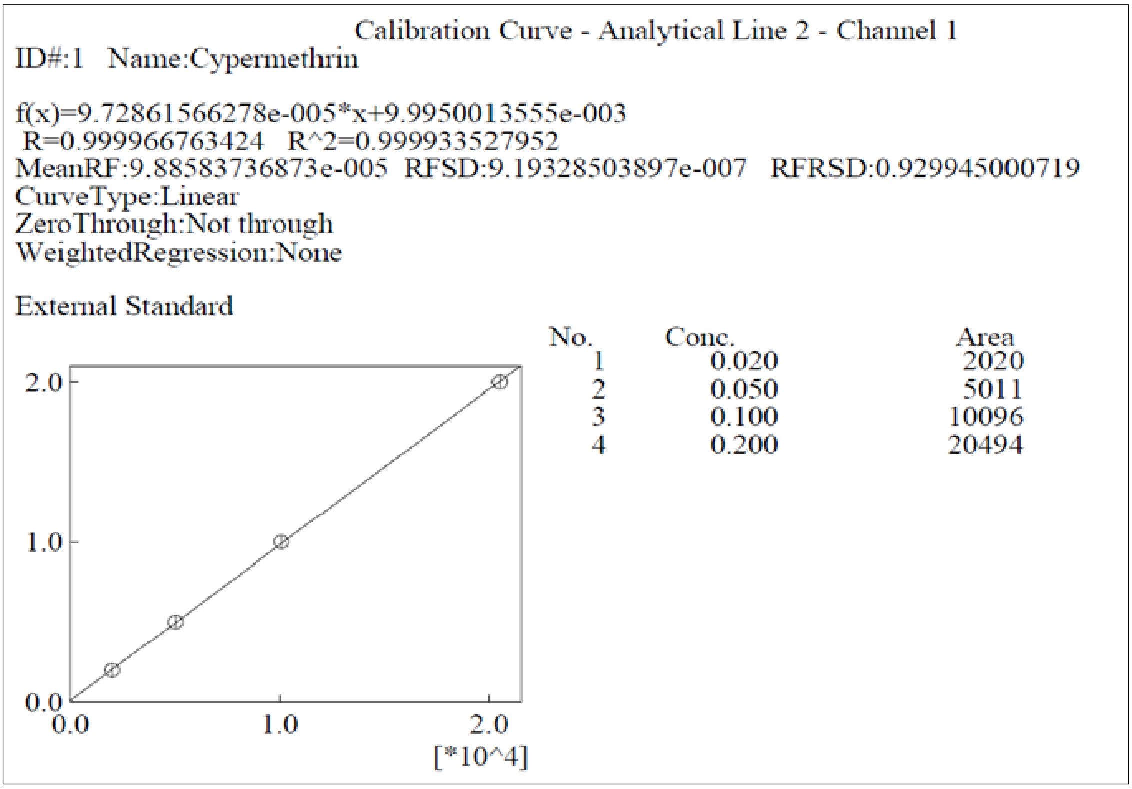

Fig. 2. Calibration curve of cypermethrin standard ranging from 0.02 mg/kg to 0.2 mg/kg.

Titratable acidity (TA %)

The 5 g sample was determined by macerating the mortar and pestle. After filtering and adding distilled water, the final capacity was 100 mL. Two drops of phenolphthalein were then added to a stock solution of 10 mL in a conical flask. Then the solution was titrated using 0.1 N NaOH. The reading was taken and the titrate will be rose pink in colour.

Ascorbic acid determination

A 5 g sample of strawberry fruit was mixed and filter paper (Whatman No. 1) was used to sieve the liquid. A solution of 5 % oxalic acid was added to get the volume up to 100 mL. The dye solution 2, 6 -dichlorophenol indophenol, was used for the titration. Using the L-ascorbic acid standard, the mean observations yielded the quantity of dye needed to oxidize a specific amount of L-ascorbic acid solution at an unknown concentration. Each time titration was performed using a 5 mL solution and the pink colour marked final point of titration, which persisted for 10 sec.

Phenolic content

Methanol (85 %) was used to homogenize 250 mg of fresh fruit. The extract was centrifuged at 10 °C for 15 min at 3000 rpm to separate the supernatant. To each 2 mL of the supernatant, Folin and Ciocalteu's reagent has been applied. Each test tube was filled with a sodium carbonate (Na_2CO_3) solution (7.5 %, 2 mL). After 30 to 45 min, the absorbance was measured at a wavelength of 725 nm. Gallic acid was used to create a standard curve to ascertain the amount of total phenols present in the unidentified sample.

Statistical analysis

Insecticide residue levels in the collected samples were measured in mg/kg using the Shimadzu GC software and all subsequent data analysis and calculations were carried out using Microsoft Excel 2021.

Results

The chromatograms of the chosen pesticide that were taken from strawberry samples at various DAS times are displayed in Fig. 3-9. The chromatogram of cypermethrin residue in strawberries taken right after spraying (0 DAS) is shown in Figure 3. At a retention time (R.T.) of 15.857 min, the GC chart displays the primary peak of cypermethrin residue.

As the number of days after spraying increased, the height of the strawberry cypermethrin residue peak reduced (Fig. 4-7). Cypermethrin's chromatogram peak at 1 DAS is depicted in Fig. 4. Its height is less than that of the 0 DAS chromatogram, but it still shows up at the same retention time of 15.857 min. The same retention period of 15.857 min was also used to observe a decreased cypermethrin chromatogram peak at 3 DAS (Fig. 5).

The chromatogram peak of the cypermethrin residue in strawberry samples taken at 5 DAS is displayed in Fig. 6. This peak's height was less than that of the 3 DAS and 1 DAS samples. Likewise, samples taken at 7 and 10 DAS showed a further decrease in peak height (Fig. 7 & 8). However, strawberry samples taken at 12 DAS did not show the chromatogram peak for cypermethrin residue (Fig. 9). This indicates that measurable levels of cypermethrin residues are no longer present in strawberries after 10 DAS.

Cypermethrin residues in strawberries

Table 1 shows the residues of cypermethrin in strawberry fruits over a 12-day period. According to the findings, the strawberries had 0.874 mg/kg of cypermethrin deposits at first. At a dosage of 0.552 mg/kg, a moderate breakdown of the pesticide residues was noted one day following application. The degradation of residues increased with the amount of time that passed after application. The initial deposits steadily declined during the experiment. Notably, ten days after spraying, strawberry fruits contained 0.043 mg/kg of cypermethrin. This suggests that 10

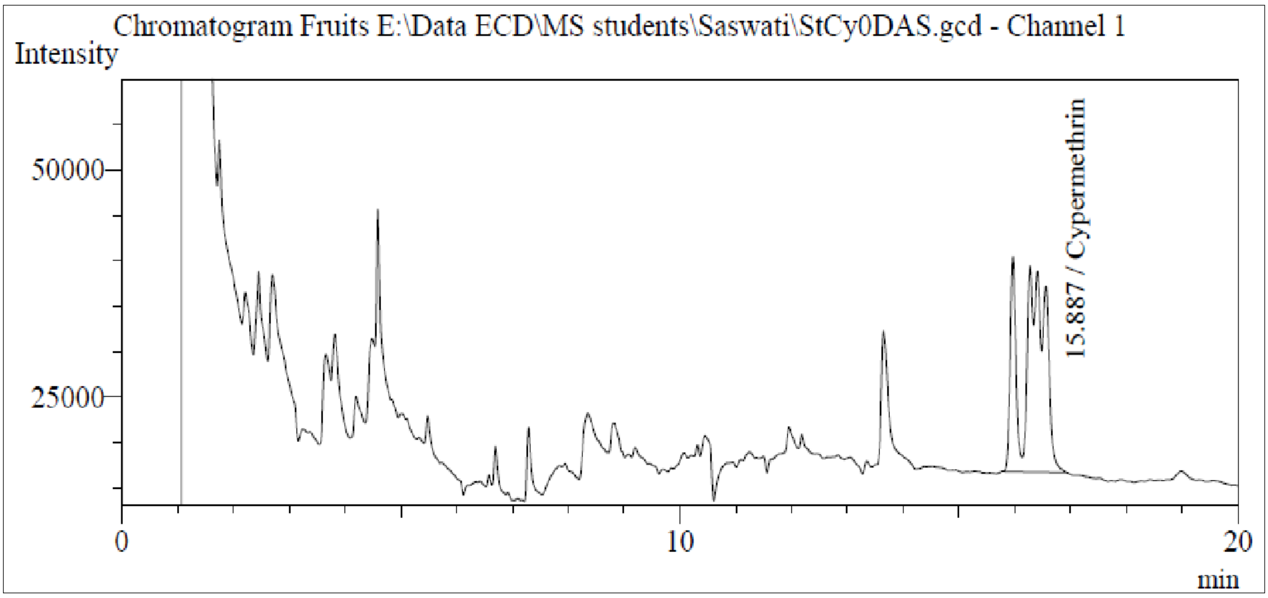

Fig. 3. Chromatogram of cypermethrin obtained from strawberry extract at 0 DAS.

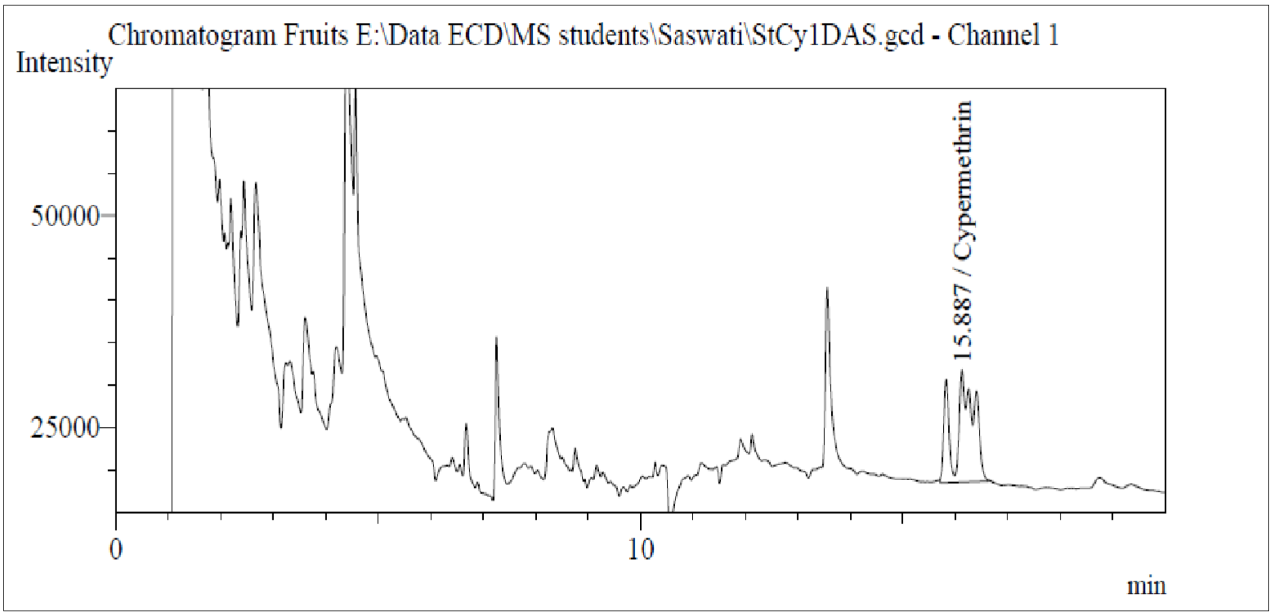

Fig. 4. Chromatogram of cypermethrin obtained from strawberry extract at 1 DAS.

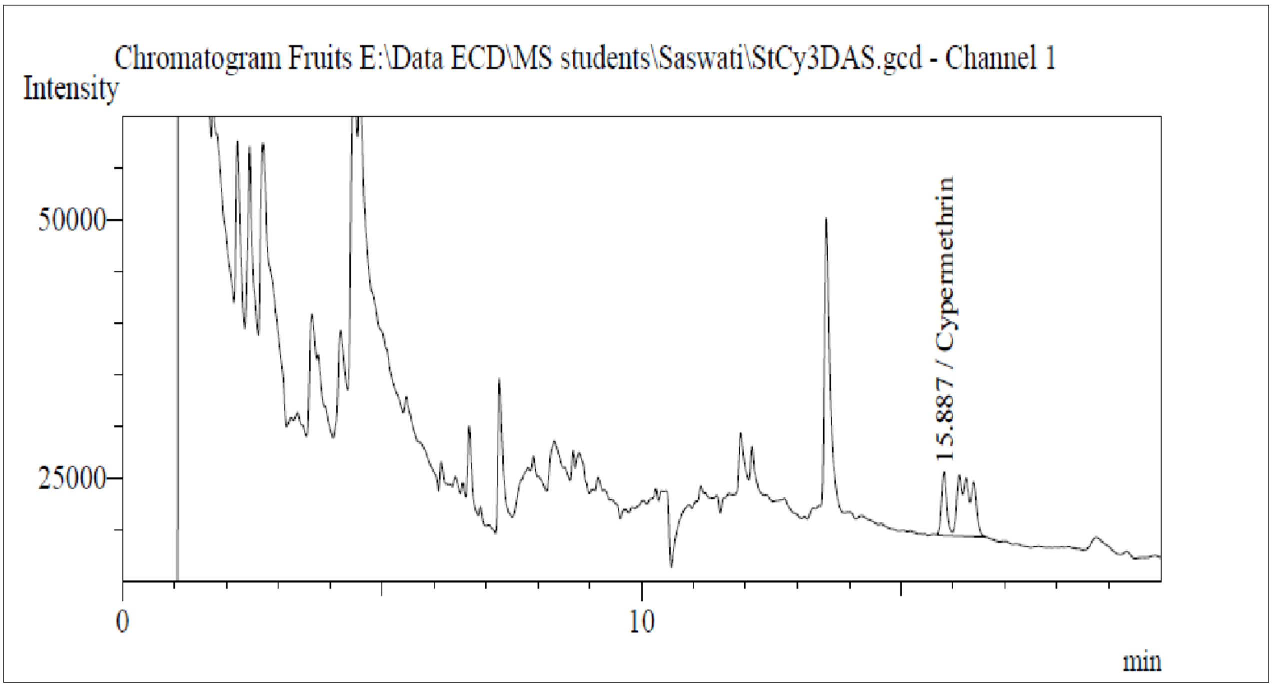

Fig. 5. Chromatogram of cypermethrin obtained from strawberry extract at 3 DAS.

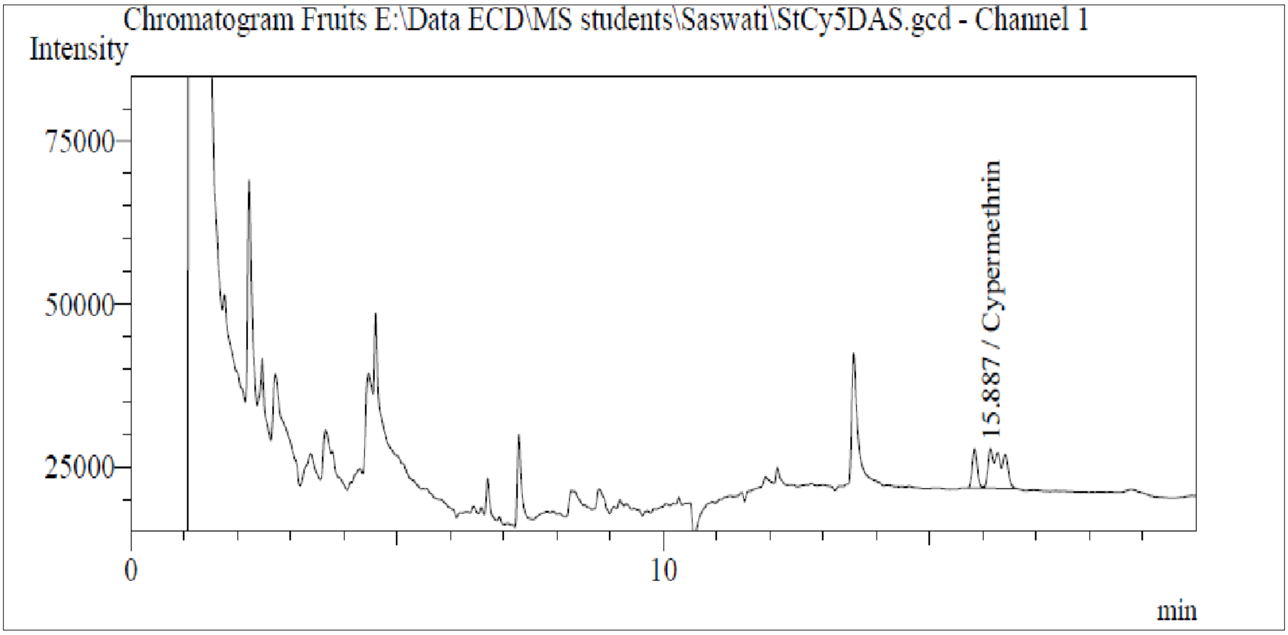

Fig. 6. Chromatogram of cypermethrin obtained from strawberry extract at 5 DAS.

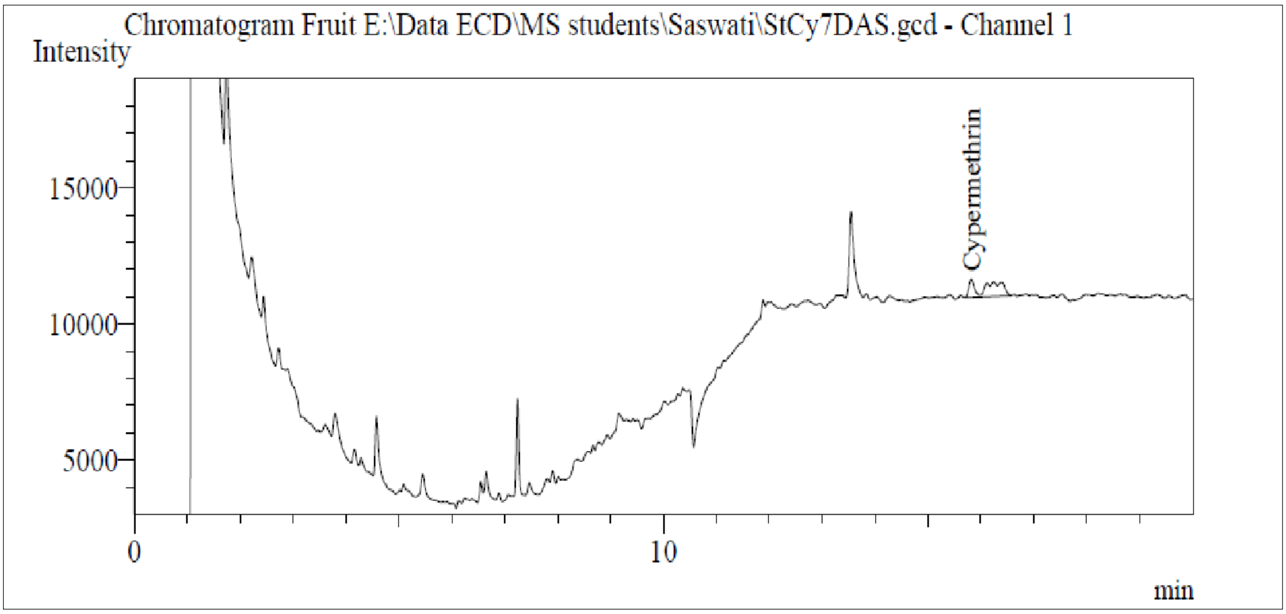

Fig. 7. Chromatogram of cypermethrin obtained from strawberry extract at 7 DAS.

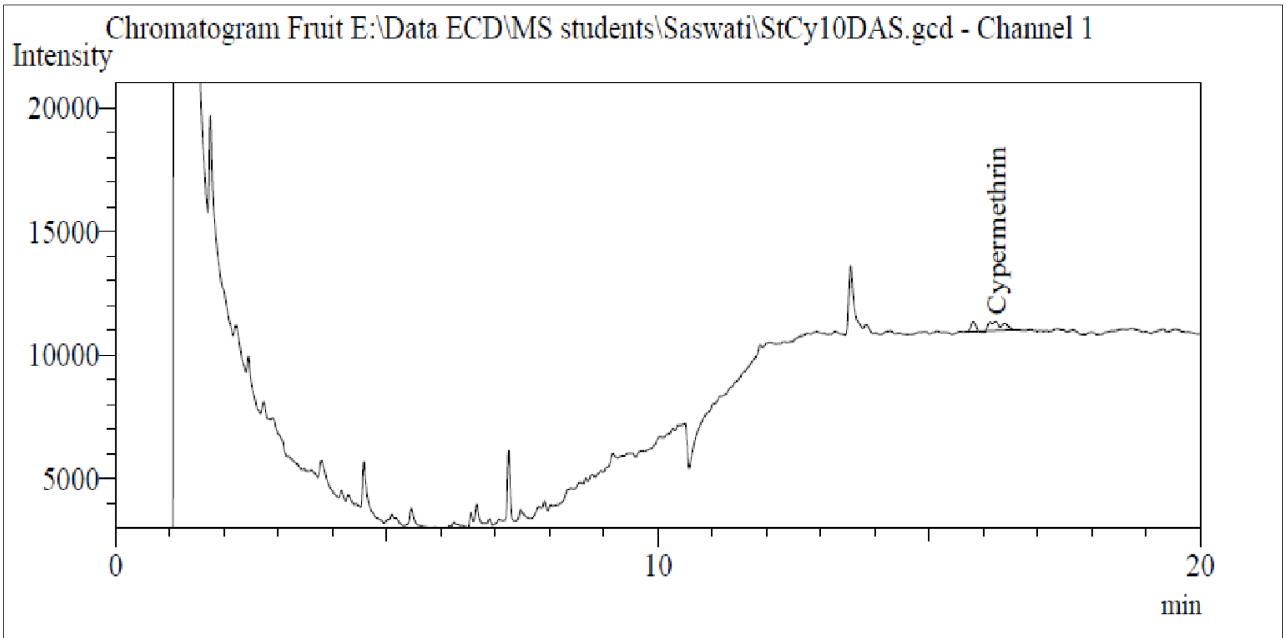

Fig. 8. Chromatogram of cypermethrin obtained from strawberry extract at 10 DAS.

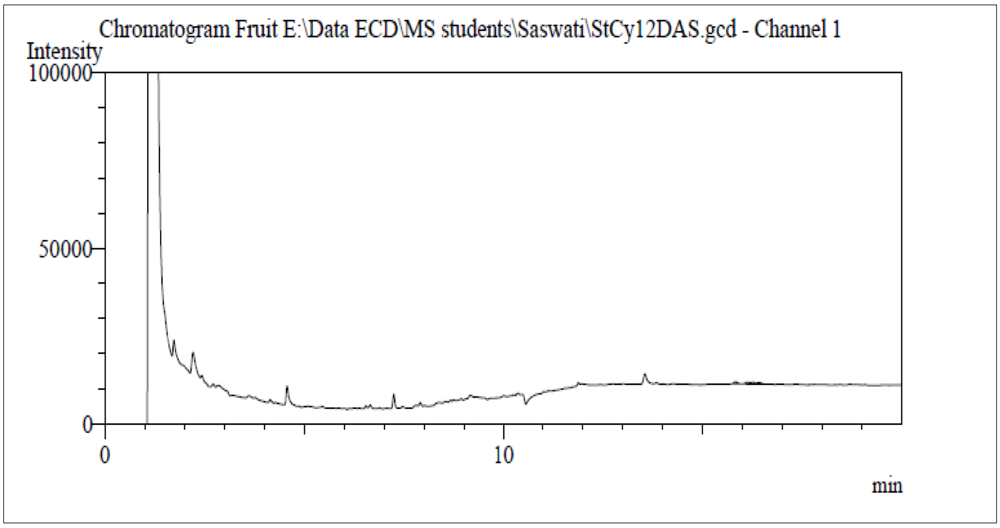

Fig. 9. Chromatogram of cypermethrin obtained from strawberry extract at 12 DAS.

days was enough time to get the cypermethrin residues on strawberries down to less than the EU Pesticides Database's MRL of 0.1 mg/kg. Consequently, ten days following cypermethrin spraying, strawberry fruits can be safely marketed for human consumption. The PHI of cypermethrin in strawberries was calculated at 10 DAS since residues in strawberries fall below MRL at that time.

Trend of residue degradation

The trend of cypermethrin residue degradation in the samples over time is depicted in Fig. 10. Despite variations in the number of residues found and the rate of degradation at different days after spraying (DAS), it demonstrates that the cypermethrin residue steadily deteriorated. The residual level at 0 DAS was 0.874 mg/kg and residues could be found up to 10 DAS.

Quality parameters

Total soluble solid (°Brix)

Pre-harvest cypermethrin spray delays the increase in total soluble solids (TSS). At 0-5 DAS, there was no significant change in TSS content in strawberries. However, TSS content of the fruit responded significantly different at different days after spraying of cypermethrin (Table 2). The TSS content was minimum in the fruits obtained from the plants at 0 DAS (5.43 °Brix), whereas the maximum was recorded from the fruits collected from 12 DAS (6.35 °Brix).

Table 1. Level of residues (mg/kg) of cypermethrin (ripcord 10 EC) found in strawberry samples

Treatments	Level of residue (mg/kg)	EU-MRL (mg/kg)
0 (2 h) DAS	0.874	
1 DAS	0.552	
3 DAS	0.309	
5 DAS	0.182	
7 DAS	0.101	0.10
10 DAS	0.043	
12 DAS	ND	

Titratable acidity (%)

Table 2 shows the trend of titratable acidity in the samples over time. The titratable acidity concentration of the fruit responded significantly differently to each DAS. It was observed that titratable acidity gradually increased up to 7 DAS, with the highest level (0.63 %) found in the fruits at 7 DAS following cypermethrin application. Nevertheless, the titratable acidity of strawberries started to decline at 10 DAS.

Ascorbic acid content (mg/100 g)

The ascorbic acid concentration of strawberry fruits throughout a 12-day period is displayed in Table 2. The ascorbic acid level of strawberries varied significantly on different days following spraying. The original ascorbic acid level was 44.16 mg/100 g, according to the data. A moderate degradation was observed one day after application, with the content decreasing to 42 mg/100 g. Ascorbic acid continued to degrade over time following treatment, progressively lowering from its original level until 7 DAS. However, at 10 DAS, the ascorbic acid concentration of strawberries began to increase.

Phenolic content (mg/100 g)

The phenolic content of strawberries varied significantly on different days after spraying. The data presented in Table 2 shows that phenolic content in the fruits gradually increased up to 7 DAS after cypermethrin application. The rate of increase varied at different DAS. One day following treatment, a modest increase in phenolic content (510 mg/100 g) was noted. At 7 DAS, the phenolic content increased the most, reaching 1034 mg/100 g. However, at 10 DAS, the phenolic content of strawberries began to decrease.

Table 2. Average content of total soluble solid, titratable acidity, vitamin C and phenolic content of strawberry extract at different days after pesticide spraying

Treatments	Ascorbic acid (mg/100 g)	Titratable acidity (%)	Phenolic content (mg/100 g)	Total soluble solid (°Brix)
0 DAS	44.16^{a}	0.28^{g}	485.7^{d}	5.43^{d}
1 DAS	42.24^{a}	0.31^{f}	510.1^{d}	5.45^{d}
3 DAS	28.80^{c}	0.35^{e}	576.2^{c}	5.55^{d}
5 DAS	27.42^{cd}	0.60^{b}	1005.7^{a}	5.70^{cd}
7 DAS	24.00^{d}	0.63^{a}	1034.5^{a}	5.90^{bc}
10 DAS	34.56^{b}	0.47^{c}	945.4^{b}	6.15^{ab}
12 DAS	37.44^{b}	0.41^{d}	599.5^{c}	6.35^{a}
CV %	7.41	1.76	2.44	2.64
LSD	4.49	0.013	31.94	0.27

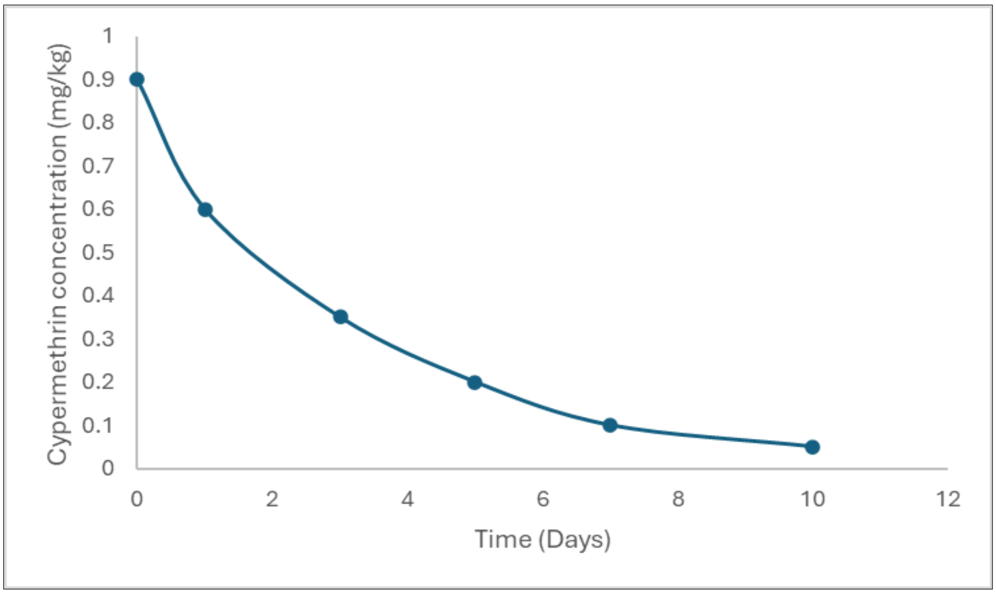

Fig. 10. The trend of degradation of detected residue of cypermethrin in strawberries over time.

Discussion

According to the findings of our investigation, cypermethrin traces were found in strawberry fruits up to 10 DAS. The level of residue that was found exceeded the maximum residue limit (MRL) until 7 DAS (0.101 mg/kg). After 12 DAS, data showed that no pesticide residues were found. The present study is in good agreement with previous studies (20). They conducted an experiment in Gujrat, India and found that cypermethrin extrapolation residues in whole sapota fruit were 0.020 mg/kg on day zero and rapidly decreased below the detection level on day ten following the last treatment. Previous studies (21) reported that on 10 DAS, a single dose of okra containing cypermethrin residues was equal to or below the determination threshold (0.01 mg/kg). Up to 5 DAS, cypermethrin residues in yard-long beans were found to be higher than the MRLs (22). The results of this investigation can also be contrasted with those of former studies (23). They found that the cypermethrin residues in the chili dropped below the detection limit (BDL) on the 7 DAS. Previous researchers reported maximal cypermethrin reduction in okra on the seventh day following application at the prescribed dosage (24). More than 90 % of initial deposits of chlorpyrifos, carbosulfan, acetamiprid and betacyfluthrin on tomato fruits disappeared after 10 DAS in an experiment conducted in Dakahlyia Governorate, Egypt (25).

There are many degradation mechanisms of cypermethrin in environment. Cypermethrin breaks down in the environment mainly through photo-degradation, microbial activity and hydrolysis, with factors such as temperature, moisture, soil type and pH affecting these processes. Although it does not remain in the environment forever, farmers should follow pre-harvest interval (PHI) of cypermethrin to ensure safe consumption of cypermethrin treated products and recommended usage guidelines to reduce its environmental impact.

Fruits and vegetables are attacked by several insects and pests at different growth stages. Farmers use heavy pesticide applications to prevent insect-pest attacks, particularly during the fruiting stage, which has been shown to leave harmful residues on fruits and soil beneath crops (26). The application of hazardous pesticides to fruits and vegetables is thought to have raised the possibility of both disease transmission and consumer poisoning (27).

Pesticides are indispensable for enhancing crop yields and combating pests in Bangladesh. Bangladesh ranks 3rd in rice and vegetable production and 10th in tropical fruits production (28). Bangladesh uses less pesticide for production compared to developed countries, but fruits and vegetables are detected with pesticide residues. The data on pesticide use per hectare across various countries reveals significant disparities, with China leading at 14.8 kg/ha, 16.6 % of the total use, European countries such as Italy (6.1 kg/ha, 6.8 %) the UK (5.5 kg/ha, 6.2 %). In contrast, lower pesticide use is observed in Bangladesh (1.8 kg/ha, 2.0 %) (29). Pesticide residue was found in over 29 % of the vegetable samples (1577); of the contaminated samples (458), the majority (73 %) had levels over the MRL (30). The underlying reason is most farmers of Bangladesh lack proper knowledge about pesticide application, recommended dose and the pre-harvest interval (PHI) of specific pesticides. They do not wait long enough for the residues to wash off after spraying before harvesting because of the high demand for farm produce and their ignorance of the negative consequences of pesticide residues in food. The pre-harvest interval, which is the period between applying pesticides and harvesting crops, is the ideal time to harvest fruits and vegetables. During this period, there is less exposure for consumers since the level of pesticide residue falls below the tolerance level set for that crop (31).

Farmers should be trained in Good Agriculture Practices (GAP). A proper pre-harvest interval time frame should be followed, after spraying pesticides on vegetables and fruits so that consumers can get residue free foods during consumption. Our results showed that the PHI of cypermethrin for strawberries was identified up to 10 DAS. Strawberries can be safely consumed 10 days after spraying cypermethrin insecticides. The decrease in pesticide residues is related to the plant's physical and chemical features, as well as its natural capacity to degrade pesticides in the environment (32). In our results, the degradation of cypermethrin in strawberry fruits was inconsistent and delayed. Cypermethrin degrades naturally in plant materials and exposure to sunlight, water and oxygen speeds up the process (33).

Spraying pesticides also affects the quality of strawberries. Pesticides disrupt plant metabolic functions, lowering food quality, as all insecticides (chlorpyrifos, carbosulfan, acetamiprid and beta-cyfluthrin) increased ascorbic acid content and TSS percent in tomato fruits when compared to untreated plants (25). The foliar spray of chlorpyrifos adversely affected the protein metabolism of

Vigna radiata L. (green gram), leading to a reduction in total protein content (34). Ascorbic acid, β-carotene, protein and total soluble solids were all considerably reduced in pepper fruits with lambda-cyhalothrin residues during the trial when compared to untreated fruits (35).

Pesticides adversely affect the metabolic enzymes responsible for the synthesis of chlorophyll and carotenoids (36). Chlorophylls and carotenoids (photoreceptor pigments) are essential in the synthesis of organic compounds like carbohydrates and proteins (37). Any disruption in their levels or activity can indirectly reduce fruit quality traits, including total soluble solids (TSS), phenolic content, ascorbic acid and titratable acidity (%). Total Soluble Solids (TSS) mainly reflects sugar content in fruits. If chlorophyll/carotenoid-mediated photosynthesis is reduced, sugar production decreases. Pesticide applications above recommended levels markedly decreased sugar content in *S. lycopersicum* (L.) roots (36). Pesticides can affect root function, limiting uptake of essential nutrients required for photosynthesis and sugar production. Many pesticides generate reactive oxygen species (ROS) in plant cells, which damage cellular components like membranes, proteins and DNA. Plants produce phenolic compounds in response to stress, which can inhibit chlorophyll biosynthesis or enhance its degradation, thereby reducing chlorophyll levels, photosynthesis and sugar formation (38). Pesticide-induced stress in plants triggers physiological and biochemical responses, including the production of reactive oxygen species and phenolic compounds, which disrupt metabolic processes such as chlorophyll synthesis and sugar accumulation. Consequently, key quality parameters such as total soluble solids (TSS), ascorbic acid and titratable acidity are indirectly reduced.

Conclusion

Cypermethrin residues in strawberry fruits declined steadily after application and were undetectable after 12 days. The initial concentration (0.874 mg/kg) exceeded the maximum residue limit (0.101 mg/kg) up to 7 DAS but fell below the MRL by 10 DAS, indicating that strawberries can be safely harvested 10 days after spraying in accordance with the PHI. These findings provide important scientific evidence on cypermethrin degradation under local agro-climatic conditions and contribute to the limited residue data available for Bangladesh. The results emphasize the need for implementing GAP, particularly strict observance of PHI, to minimize pesticide residues and ensure food safety. However, this study was limited to one pesticide and a single cropping season. Future research should evaluate multi-seasonal variations, different pesticide formulations and environmental factors influencing residue dissipation to strengthen safe-use recommendations and sustainable strawberry production.

Acknowledgements

The National Agricultural Technology Program Phase-II Project (NATP-2), Bangladesh, provided financial assistance for the current study. The authors also express their gratitude to the Bangladesh Agricultural Research Institute (BARI), Gazipur's Pesticide Analytical Laboratory, Entomology Division, for helping them analyse the samples.

Authors' contributions

SE conducted field and laboratory experiments, collected the data and drafted the manuscript. MZI, MNI, SY, MDHP and SC contributed to the experimental design, coordination and revision of the manuscript. All authors read and approved of the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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