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REVIEW ARTICLE

Review on poisonous pesticides dissipation pattern and their residual effects in cardamom

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Abstract

Cardamom (*Elettaria cardamomum*), a high-value spice crop, is often subjected to intensive pesticide applications to combat pests and diseases. However, the use of toxic pesticides raises significant concerns regarding their dissipation patterns and residual effects on the ecosystem, harvested produce and human health. This review examines the fate and behavior of toxic pesticides in cardamom cultivation, focusing on their application methods, degradation kinetics and persistence in soil, water and plant tissues. Factors influencing pesticide dissipation such as environmental conditions, soil properties and microbial activity are critically analyzed. The long-term residual impacts on cardamom quality, non-target organisms and consumer safety are also discussed. Furthermore, the review highlights existing regulatory limits, analytical detection methods and potential mitigation strategies to minimize pesticide residues in cardamom. By utilizing existing research, this paper aims to provide insights into sustainable pest management practices that reduce reliance on hazardous chemicals while maintaining ensuring crop productivity and ensuring food safety.

Keywords: cardamom; degradation; dissipation; environment factor; mitigation strategies; pesticide residues; suitable pest management

Introduction

Often referred to as the "Queen of Spices" cardamom (*Elettaria cardamomum*) is primarily grown in India, Sri Lanka and Guatemala (1). The use of chemical pesticides in its cultivation has become an integral part due to its high economic value and susceptibility to various pests and diseases (2). However, the application of toxic pesticides, serious concerns regarding environmental contamination, food safety and human health (3). A variety of pesticides, including organophosphates, carbamates, neonicotinoid pesticides and synthetic pyrethroids, are commonly used in cardamom plantations to control pests, such as thrips, borer insects and aphids (4). While these agrochemicals contribute to increased yield and improved crop quality, their persistence in soil, water and harvested produce poses serious risks (5). Factors influencing pesticide dissipation include weather conditions, soil properties, plant metabolism and the chemical structure of pesticide, all of which determine the degradation rate and residual impact (6). Cardamom that contains pesticide residues exceeding permissible limits poses serious concerns for consumer safety and compliance with export regulations (7). Chronic exposure to residual pesticides may lead to long-term health risk, including neurotoxicity, endocrine disruption and cancer (8). Moreover, the overuse of pesticides adversely affects beneficial soil microbes, pollinators and overall biodiversity (9).

This review aimed to provide a comprehensive overview of the types and sources of poisonous toxic chemical pesticides presently used in cardamom cultivation, examine their application trends and dissipation behaviour and prospects for long-term residual effects on the environment and human health. It also seeks to explores sustainable alternatives and regulatory strategies to for reduce pesticide-related risks in cardamom cultivation (10).

Pesticides used in cardamoms

In cardamom cultivation, insecticides are widely used to control a variety of pests that can significantly impact both yield and crop quality. Table 1 presents a list of commonly used insecticides in cardamom farming, categorized according to their chemical class and mode of action.

Dissipation patterns of pesticides in cardamom

Pest pressure and environmental conditions significantly influence the quantity of pesticides utilized in cardamom production. To achieve efficient pest management while reducing their negative effects on the environment, farmers usually follow specified pesticide usage standards, including dosage and timing. However, there may be instances where these guidelines are not followed due to factors such as several pest outbreaks, unpredictable weather conditions, or a lack of awareness (11).

Pesticides in cardamom farming are applied in several ways, including dusting, soaking and spraying. The choice and execution of the application method can substantially affect both the efficacy of pest control and the environmental impact of pesticide use. For instance, inefficient spraying techniques may result in uneven coverage, thereby reducing effectiveness and increasing the risk of pesticides runoff into nearby ecosystems (12).

Adopting Integrated Pest Management (IPM) strategies and utilizing environmentally friendly options, like bio-pesticides, can reduce reliance on chemical pesticides and minimize their effects on the environment (13). Moreover, comprehensive training and awareness initiatives for farmers are crucial to ensure adherence to best practice and promote sustainable cardamom cultivation (14).

Factors influencing dissipation

The dynamics of pesticide dissipation in cardamom cultivation are governed by a multifaceted interaction of environmental, chemical and biological factors. Environmental conditions such as temperature, humidity, precipitation and soil characteristics significantly influence the degradation rates and persistence of pesticide residue within ecosystems. Furthermore, the intrinsic chemical properties of pesticides, including their half-life, solubility- and volatility, critically influence their behavior and mobility in the environment (15). The degradation of pesticide residues is also significantly affected by microbial activity in the soil and the metabolic processes of within cardamom plants (16). An comprehension understanding of these factors is essential for accurately predicting pesticide persistence, reducing environmental contamination and ensuring the safety and quality of cardamom as an edible commodity (17).

Environmental factors influencing dissipation

Temperature

Elevated temperatures typically expedite the degradation of pesticides by promoting chemical reactions and stimulating microbial activity with the soil (18). For example, organophosphate pesticides, such as chlorpyrifos, degrade more rapidly in warmer climates due to increased hydrolysis and heightened microbial metabolism (19). In contact, lower temperatures tend to slow processes, thereby prolonging the persistence of pesticide residues in the environment (20). Temperature variations also influence pesticide volatilization, temperatures increase likelihood of pesticides to evaporating into the atmosphere (21). Comprehending the influence of temperature is crucial for forecasting pesticide dynamics, optimizing application timing and reducing risks to both environment and human health. Research indicates the elevated temperatures accelerate infinity microbial activity and promote chemical degradation thereby accelerating, pesticide breakdown (22). For example, studies have shown that in cooler regions (15-20 °C), monocrotophos residues persisted for up to 30 days, whereas in warmer regions (25-30 °C), residues dissipated within 15 days, emphasizing. The role of temperature in regulating pesticide half-life (23). Additionally, volatilization losses of cypermethrin increased by 40 % at temperatures above 35 °C in compared to those at 25 °C, leading-to lower residue concentrations on cardamom plants but contributing significantly to atmospheric contamination (24).

Humidity

High humidity accelerates pesticide dissipation by promoting hydrolysis and enhancing microbial degradation pathways. Experimental studies have shown that, quinalphos residues degraded 60 % faster in humid regions (relative humidity > 75 %)

Table 1. Commonly sprayed insecticides in cardamom farming

	Chemical name	Target pest	Residual concern	Reference
Organophosphates	Chlorpyrifos	Borer, thrips, shoot flies	High persistence in soil and water; toxic to non-target organisms.	(78)
	Quinalphos	Capsule borer, root grub		(4)
	Monocrotophos	Sucking pest like aphids and thrips		(79)
Synthetic pyrethroids	Cypermethrin	Thrips, shoot borer, capsule borer	Low persistence in the environment but highly toxic to bees and aquatic life.	(78)
	Deltamethrin	Sucking and chewing pests		(80)
	Lambda-cyhalothrin	Broad spectrum of insects		(40)
Carbamates	Carbaryl	Thrips, aphids, mites	Moderate persistence; toxic to birds and beneficial insects.	(81)
	Carbofuran	Soil-dwelling pests like root grubs		(82)
Neonicotinoids	Imidacloprid	Sucking pests like aphids, thrips, whiteflies	Systemic action leads to residues in plant tissues; harmful to pollinators.	(25)
	Thiamethoxam	Wide range of pests		(25)
Biological Insecticides	Neem-based products (Azadirachtin)	Thrips	Environmentally friendly with minimal residual effects.	(83) (84)
	Bacillus thuringiensis (Bt)	Caterpillars and borers		
	Beauveria bassiana	Thrips and borers		
Organochlorines	Endosulfan	Borers, sucking pests	Highly persistent in the environment; bioaccumulates in the food chain.	(25)
Insect growth regulators (IGRs)	Buprofezin	Sucking pests like thrips and whiteflies	Low toxicity to non-target organisms.	(85)
	Lufenuron	Immature stages of insects		(86)

compared to arid zones, primarily due to increased hydrolysis (25). Similarly it was observed that chlorpyrifos hydrolysis rates increased significantly under high humidity (> 80 %), reducing its half-life from 30 days to 10 days, with *Pseudomonas* spp. contributing to a 40 % enhancement in degradation (26). In contrast, monocrotophos displayed prolonged persistence under low-humidity conditions, with a half-life of 25 days at 40-50 % RH - compared to just 10 days at 80-90 % RH, highlighting the critical influence of humidity on microbial degradation processes (27). Furthermore under high humidity conditions, cypermethrin adsorption onto soil organic matter by 70 % while simultaneously accelerating surface hydrolysis, illustrating dual role of humidity's on pesticide behavior (5). Although humidity promotes degradation in many cases, it can also contribute to persistence, depending on the chemical structure of the pesticide and its interaction with soil microbial communities (28).

Rainfall

High rainfall facilitates pesticide dissipation through mechanisms such as leaching, surface runoff and enhanced microbial activity, while low rainfall prolongs residue persistence by inhibiting these processes. For instance, under condition of heavy rainfall (>150 mm/month), monocrotophos residues in cardamom fields were reduced by 40 % (7). Similarly, intense rainfall (>100 mm/month) reduces chlorpyrifos residues by 50 % through leaching and runoff. However, this reduction correlates with elevated water contamination risks, as pesticides displaced from soil can enter aquatic ecosystems (29). In addition to physical transport, microbial degradation of imidacloprid doubled under high-rainfall conditions (>150 mm/month), driven by moisture sensitive microbial taxa such as *Burkholderia* and *Streptomyces*. This dual effect enhanced degradation paired with increased environmental risks is further exemplified by studies quantifying the combined effects of leaching and microbial activity. For instance, monsoon rainfall (>200 mm/month) reduces pesticide residues in cardamom capsules by 30 %, though efficacy varies with soil texture and compound solubility (30-33).

Sunlight

Sunlight, particularly ultraviolet (UV) radiation, significantly contributes to pesticide dissipation in cardamom cultivation through photodegradation, breaking down toxic compounds into less harmful by products. UV exposure reduced cypermethrin residues on leaves by 70 % compared to shaded conditions, highlighting the vulnerability of synthetic pyrethroids, which degrade two-three times faster under direct sunlight (34, 35). However, photodegradation efficiency depends on pesticide chemistry (e.g., presence aromatic rings), sunlight intensity and duration of exposure. More stable compounds, such as neonicotinoids, exhibit resistance to photolysis (36). Although sunlight facilitates pesticide breakdown, a study highlights a critical trade-off: photodegradation can produce toxic transformation products, such as hydroxylated chlorpyrifos derivatives, which adversely affect soil microbiota (37). This underscores the need for comprehensive lifecycle assessments of agrochemicals. The interplay between sunlight and pesticide fate informs strategies for residue management while ensuring crop health. For instance, partial shading (using 50 % shade nets) optimized cardamom yield and flavor by reducing pest pressure, whereas full sun exposure increased both irrigation demands and the volatility of photodegradation (38). Complementing this, a study linked high light interception to elevated leaf temperatures and transpiration rates (40 % higher in summer compare to the monsoon season), stressing the need of climate-smart canopy management (39).

Soil type

Soil classification plays a pivotal role in determining pesticide dissipation dynamics within cardamom agro ecosystems by influencing adsorption, degradation and leaching processes. As demonstrated in study, sandy soils exhibit low adsorption capacity, which accelerates pesticide leaching, reducing chlorpyrifos surface residues by 50 % compared to clay soils, while simultaneously increasing leaching risks by 70 % (40, 41). Similarly, soils rich in organic matter enhance microbial degradation efficiency. Soil hydrology introduces additional variability: water-logged conditions have been shown to double degradation rate of quinalphos (50 % faster) than in dry soils, likely due to anaerobic microbial activity (42). Soil structure also plays a dual role. Well-aerated soils facilitated cypermethrin degradation by 25 % more than compacted soils, where restricted water infiltration suppressed microbial activity. This findings aligns with reports, indicating a 30 % increase in quinalphos persistence in compacted soils, highlighting how poor soil structure hampers both physical and biological dissipation mechanisms (43).

Chemical properties of pesticides

The environmental behaviour and ecological impact of pesticides in cardamom ecosystems are fundamentally governed by their intrinsic chemical properties, including half-life, solubility, volatility, adsorption coefficient (Koc) - and degradation pathways. These properties dictate whether pesticides persist in soil, volatilize into the atmosphere, adsorb to organic matter or leach into groundwater, thereby shaping their potential to degrade soil health contaminate water sources, or accumulate in harvested crops. For example, highly water-soluble compounds such as imidacloprid (water solubility: 610 mg/L) exhibit pronounced leaching tendencies, elevating risks of aquifer contamination, whereas volatile pesticides like cypermethrin (vapor pressure: 1.7×10^{-5} mmHg) tend to evaporate quickly, reducing foliar residues but contributing to atmospheric pollution. Similarly, pesticides with high Koc values (e.g., fipronil; Koc = 727-980) exhibit strong adsorption to soil organic matter, which prolongs their persistence in the field while simultaneously limiting their bioavailability. A comprehensive understanding of these chemical traits is essential for formulating application strategies that optimize pest control while environmental impact, ultimately safeguarding sustainability of cardamom as a globally traded spice.

Half-life

The environmental persistence and ecological risks of pesticides are largely determined by their half-life-the time required for 50 % of a compound to degrade. Pesticides with short half-lives (<30 days) degrade rapidly, there by minimizing long-term environmental impact, In contrast, compound with extended half-lives (>100 days) tends to accumulate in soil, water and plants, increasing the risk of biomagnification risks. Chlorpyrifos, a common insecticide in cardamom farming-has a soil half-life of 30-60 days, enabling moderate leaching but necessitating repeated applications. In contrast, highlights that DDT, despite being widely banned, persists in the environment for 2-15 years due to its hydrophobic stability, demonstrating the enduring hazards of persistent agrochemicals (4). These disparities, as evidenced by a study underscores the need for half-life-informed regulations to balance agricultural productivity and ecological safety (43).

Solubility

Water solubility plays a crucial role in determining the fate of pesticide. High solubility enhances the potential for leaching as seen with imidacloprid, (610 mg/L), while low solubility compounds, such as (DDT, 0.025 mg/L), tends to persist by adsorbing to soil particles. Soluble pesticides like imidacloprid poses a higher risk of groundwater contamination, whereas hydrophobic pesticides like DDT increases the risk of terrestrial bioaccumulation (6). risk groundwater contamination due to mobility, whereas hydrophobic DDT persists, elevating terrestrial bioaccumulation (6). These solubility-driven trade-offs necessitate tailored mitigation-monitoring runoff for soluble compounds and long-term soil remediation for persistent ones (6).

Volatility

Volatility-the tendency of a pesticide to evaporate-also influences environmental persistence. Highly volatile compounds, such as cypermethrin, reduce surface residue levels but contribute significantly to airborne contamination. Conversely, pesticides with low volatility persist longer in soil and water environments. These contrasting, outcomes necessitate volatility-informed application practices to maintain efficacy while minimizing ecological risks (44).

Adsorption coefficient (koc)

The adsorption coefficient (Koc) indicates a pesticides' binding affinity to soil particles, which governs its mobility and persistence. For instance glyphosphate, with a high Koc value (900-20000 mL/g), binds strongly to organic matter, minimizing leaching a extending its activity on soil surfaces (45).

Hydrolysis

Unstable The stability pesticides under moist conditions is critical factor in their environmental behaviour. Compounds like monocrotophos degrade rapidly through hydrolysis in humid environment, while more stable pesticides, such as neonicotinoids, exhibit prolonged environmental retention. These variations highlights the need for application strategies that consider local humidity levels (46).

Photodegradation

UV-driven Photodegradation, driven by ultraviolet (UV) radiation, significantly influences the residual durability of pesticides. Compounds such as cypermethrin undergo rapid breakdown under sunlight, necessitating strategic scheduling of applications to balance efficacy and environment safety (47, 58).

Molecular weight

Pesticides persistence is often associated with molecular complexity. Higher molecular weight compounds like DDT exhibit prolonged environmental stability due to their intricate structures. In contrast, simpler molecules, such as carbaryl, degrade more quickly. This relationship serves as a foundation for designing more sustainable pesticides formulations (48).

Degradation pathways

Pesticides The role of pesticides dissipation also depends on the number and type of degradation pathways. Pesticides such as imidaclorpid, which degrade through both microbial and chemical mechanisms, tend to dissipate faster than those like DDt, which rely primarily on photolytic breakdown. This has been demonstrated in multiple studies (49).

Dissipation in plant tissues

The dissipation of pesticides in plant tissues refers to the processes through which pesticide residues break down or are removed from the plant following application. This phenomenon is influenced by various factors, including the chemical characteristics of pesticides, plant physiology and prevailing environmental conditions.

Uptake of pesticides

Root uptake

The uptake and translocation of pesticides in plants-critical to residue dynamics-are governed by both the chemical properties of the pesticides and plant physiology. Water-soluble pesticides, such as imidacloprid are absorbed through roots via passive diffusion whereas systemic compounds may also be absorbed foliar through cuticles or stomatal pathways (34). Neonicotinoids demonstrate bidirectional movement within the plant via xylem facilitating widespread internal residue distribution (50). In contract pesticides remain largely surface-bound, exhibiting limiting mobility (34). These uptake mechanisms are strongly influenced by factors such as solubility, molecular size and environmental conditions, including soil moisture. In cardamom cultivation, precise optimization of application timing and pre-harvest intervals is essential to minimize residue levels while maintaining effective pest control (34).

Foliar uptake

Foliar uptake of pesticides-critical for systemic efficacy-involves two primary pathways: cuticular penetration and stomatal entry (51). As shown in several experiments, pesticides diffuse through the waxy cuticle via passive diffusion, while stomatal uptake predominates under humid conditions, where moisture-induced pore dilation facilitates entry. Leaf morphology significantly influences pesticide uptake, with waxy or hairy surfaces (e.g., cardamom leaves) reducing absorption by 40-60 % compared to smooth surfaces. Conversely, optimized pesticide formulations enhance penetration through adjutants such as surfactants, which lower surface tension to improve cuticular diffusion a critical factor for compounds like cypermethrin. Although cypermethrin primarily acts as a contact pesticide, partial cuticular penetration occurs under high humidity, reflecting the interplay between environmental conditions and chemical properties. These findings highlight the importance of tailoring pesticide formulations to balance efficacy and residue reduction in crops such as cardamom (51).

Translocation pathways

Synthetic pesticides move systemically via xylem (transpiration-driven) or phloem (targeting young tissues), with efficiency shaped by solubility (e.g., imidacloprid) and plant traits (e.g., cardamoms' transpiration). Root applications of imidacloprid, for example, translocate to leaves and capsules, balancing pest control and reduced environmental impact (52). Non-synthetic pesticides, in contrast, exhibit localized behavior: contact compounds such as cypermethrin persist at application sites, forming surface residues that enable targeted pest management. However, due to their limited systemic movement, such pesticides require precise application timing and frequent reapplication to maintain efficacy- an approach that reduces systemic residues but demands consistent management. translocation (53).

Factors influencing uptake and translocation

a) Pesticide chemical properties- Chemical attributes such as solubility, molecular size, polarity-govern plant uptake and translocation of pesticides. Water-soluble (e.g., imidacloprid) and smaller molecules absorb efficiently; polar compounds translocate via xylem, non-polar via phloem, critically shaping agricultural efficacy and environmental behavior.

b) Plant physiology: It critically influences pesticide behavior in cardamom cultivation. Extensive root systems enhance pesticide uptake from soil, while high transpiration rates facilitate systemic transport of pesticide via xylem pathways. Moreover, active metabolic processes accelerate pesticide breakdown and redistribution, particularly reducing residue accumulation in cardamom capsules. These interconnected processes support both pest and environmental dissipation (39).

c) Environmental conditions critically shape pesticide behavior: soil moisture enhances root uptake by solubilizing pesticides (42), while elevated temperatures boost transpiration-driven translocation (43). These factors collectively optimize pesticide efficacy while underscoring climate-aware application strategies and high humidity promotes stoma-tal-mediated foliar absorption (42, 54).

Residue distribution

Foliar exposure results in the highest pesticide residues in leaves, while stem residues are reduced by inefficient translocation (55). Capsules accumulate systemic pesticides applied during flowering, posing food safety risks (56). Root residues correlate with application methods and uptake efficiency, with systemic pesticides like imidacloprid translocations above-ground tissues (57). Understanding these residue distribution patterns is crucial for optimizing pesticide use and ensuring compliance with safety standards. Understanding these patterns is critical for optimizing application strategies and ensuring regulatory compliance (55).

Adherence to Maximum Residue Limits (MRLs) in cardamom capsules ensures food safety, safeguarding consumers while meeting regulatory requirements (58). Systemic pesticides like imidacloprid provide sustained pest control through uniform tissue distribution (59). Moreover, a thorough understanding of pesticide translocation mechanisms can help reduce off-target effects on pollinators and other beneficial organisms (34). Thus, striking a balance between pest control efficacy food safety and ecological stewardship in vital in cardamom cultivation (58).

Degradation pathways

Pesticide degradation rates vary across cardamom plant tissues- leaves tends to degrade residues more rapidly due to exposure to UV-driven photodegradation and enzymatic activity, Whereas stems exhibit delayed degradation because of lower UV exposure and limited enzymatic activity (59). Capsules primarily degrade pesticide residues through hydrolysis, microbial metabolism and environmental interactions. Systemic pesticides like imidacloprid, which accumulate during flowering, tend to degrade slowly, necessisting carefully timed applications to comply with safety limits (60).

Dissipation in Soil

The dissipation of pesticides in soil is a critical process that determines their persistence, mobility and environmental impact in cardamom cultivation. This process involves several key mechanisms, including adsorption, degradation, leaching and volatilization. All of which are influenced by factors such as soil characteristics such as texture, organic matter content, microbial activity and prevailing environmental conditions.

Adsorption

Binding of pesticides to soil particles (e.g., organic matter, clay)- reduces mobility and leaching (61). Soil rich in clay and organic material exhibits higher adsorption capacity than sandy soils. For example chlorpyrifos, strongly binds to clay/organic soils, minimizing groundwater contamination risks (61). These interactions significantly affect pesticide persistence and environmental safety in cardamom ecosystems (61).

Leaching-the downward movement of water-soluble pesticides through soil profiles-poses a major threat to groundwater quality, particularly in sandy soils with low adsorption capacity (34). Heavy rainfall further exacerbates this process by enhancing pesticide dissolution and mobility. Highly soluble pesticides, such as imidacloprid, are especially prone to leaching in permeable soils (34). Therefore soil-specific pesticide application practices are necessary to mitigate contamination in cardamom cultivation (34).

Microbial degradation

Microbial degradation is a key mechanism for pesticide dissipation in cardamom-growing soils. Soil microorganisms - including bacteria, fungi and actinomycetes - degrade pesticides enzymatically into less toxic metabolites. The efficiency of biodegradation is influenced by factors such as soil type, organic matter content, moisture levels, temperature and the chemical nature of pesticide (62).

For example, experiments have demonstrated that chlorpyrifos degrades via microbes into 3,5,6-trichloro-2-pyridinol (TCP), while monocrotophos show faster degradation in organic-rich, microbial active soils. The study highlight practices like organic amendments and optimal soil conditioning to enhance microbial activity, reducing pesticide persistence and ecological risks in cardamom systems (62).

Dissipation in water

Pesticides dissipate in water via hydrolysis, sunlight and microbial activity. However persistent compounds like DDT) resist breakdown, accumulating in ecosystems. Runoff and leaching-especially during heavy rainfall or in poor soils with poor- adsorption-facilitates the movement of pesticides like imidacloprid into aquatic systems. Risk mitigation demands careful pesticide selection and proper irrigation management to minimize aquatic contamination (63).

Pesticides used in cardamom cultivation, such as imidacloprid and chlorpyrifos, contaminate aquatic ecosystems via runoff, as demonstrated in studies, which link these chemicals to neurotoxicity, reproductive impairment and mortality in fish, amphibians and invertebrates. Moreover, persistent pesticides like DDT bio accumulate through aquatic food webs, threatening higher tropic levels (e.g., birds, mammals) reliant on contaminated prey (64). Fig. 1 illustrates the multi-state breakdown of pesticides in cardamom agroecosystems, highlighting key enzymatic processes (e.g., hydrolysis, oxidation) and mitigation strategies such as the use of biochar and microbial consortia.

Detection methods of pesticides residues

Analytical techniques

Pesticides residues in cardamom can adversely affect the nervous, endocrine and reproductive systems. Moreover, these residues negatively impact ecosystems by harming non-target organisms, degrading water quality and compromising soil health and overall environmental integrity. Accurate detection of pesticide residues in cardamom is essential for ensuring food safety and meeting regulatory standards (58). Gas Chromatography-Mass Spectrometry (GC-MS) separates volatile compounds (e.g., organophosphates, pyrethroids) and identifies them via mass spectrometry, offering high sensitivity and specificity (58). For example, chlorpyrifos and cypermethrin residues in capsules were quantified using GC-MS, along with quantification of monocrotophos in leaves and endosulfan in soils samples (65). These applications validate the value of GC-MS as a gold standard for multi-residue analysis in cardamom systems (65).

Regulatory compliance

Pesticide residue levels in cardamom capsules at the time of harvest are influenced by factors such as pesticide type, application timing and pre-harvest intervals (PHIs) (4). Chlorpyrifos residues can exceed (MRLs) if the crop is harvested prematurely (4). Post-harvest processing such as washing, drying facilitates degradation through photodegradation and volatilization processes (66). However, systemic pesticides like imidacloprid can persist even after theses post-processing steps, necessitating the importance of careful pesticides selection and cautious selection and strict PHI adherence (67). Consistent monitoring of pesticide during both harvest stages is critical to ensures consumer safety and to comply with global trade compliance (4).

Residual effects of pesticides

Impact on soil health

Pesticide residues in cardamom soils disrupt microbial communities, nutrient cycling and overall soil fertility, with persistent pesticides like chlorpyrifos and DDT accumulating and harming beneficial microorganisms (68). Prolonged use of organophosphate reduces populations of nitrogen-fixing bacteria and mycorrhizal fungi, directly impairing soil fertility (68). Additionally, pesticides residues can alter soil pH and reduce organic matter (68). The adoption of sustainable agricultural practices like (IPM) and organic amendments mitigate these effects, restoring soil health (69). Striking the balance between effective pest control with and agroecological stewardship is essential to ensures the long-term sustainability of cardamom cultivation systems (68).

Accumulation of toxic residues

Pesticide residues accumulating in soil, plant tissues and water bodies pose serious long-term environmental and health risks. Persistent organochlorines (e.g., DDT) and organophosphates (e.g., chlorpyrifos) resist degradation due to slow breakdown rates (70). In soil, these residues disrupt microbial communities and nutrient cycling, reducing both fertility and crop productivity (70). As shown in a study residues accumulate in cardamom leaves, stems and capsules, often exceeding and threatening consumer safety (71). Additionally, runoff and leaching transport residues into aquatic ecosystems, where bioaccumulation risks contaminate food chains, as demonstrated in (72). Collectively, a study underscore the urgency of adopting sustainable practices

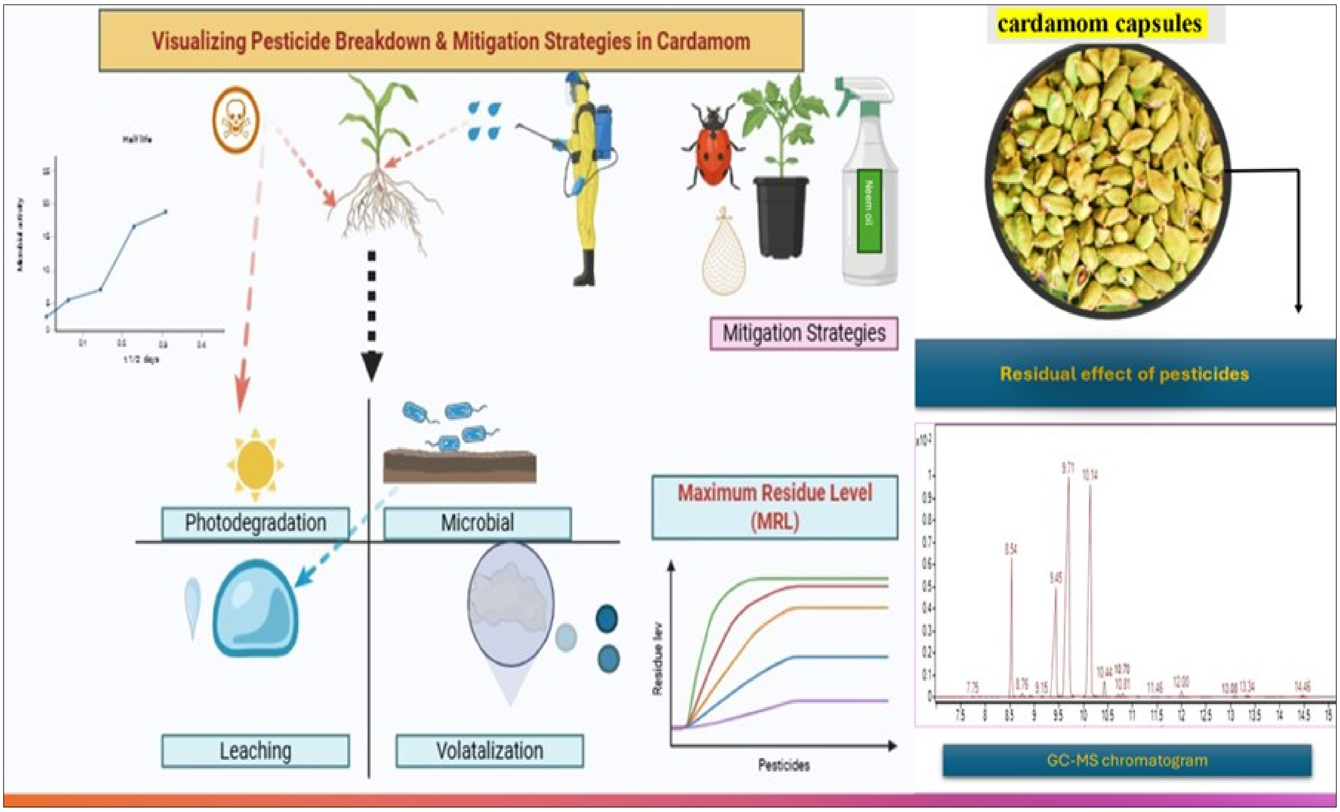

Fig. 1. Visualizing pesticides breakdown and mitigation strategies in cardamom.

like IPM and rigorous residue monitoring to mitigate ecological and health impacts (70). Pesticides residues harmful to beneficial insects are listed in Table 2.

Effect on soil microbiota and fertility

Pesticide residues in soil under cardamom-growing soils profoundly disrupt soil microbiota and fertility, threatening long-term agricultural sustainability. As demonstrated in a study, persistent pesticides like chlorpyrifos (organophosphate) and DDT (organochlorine) accumulate in soils, suppressing nitrogen-fixing bacteria (e.g., Rhizobium, Azotobacter), mycorrhizal fungi and decomposers essential for nutrient cycling (73). A study found that chlorpyrifos residues reduce Rhizobium and Azotobacter populations by 40-60%, directly impairing nitrogen fixation and soil fertility (74). Additionally, residues alter soil pH and organic matter content, further destabilizing microbial activity and nutrient availability (73), which escalates reliance on chemical fertilizers and diminishes crop yields over time. To counter these effects, (75) advocates sustainable practices-organic farming, crop rotation and IPM-to rejuvenate soil health and break dependency on agrochemicals. Collectively the study underscore the urgency of integrating ecological practices to safeguard soil ecosystems in cardamom cultivation (73).

Effect on non-target organisms

The residual effects of pesticides in cardamom cultivation disproportionately harm non-target organisms, destabilizing ecological balance (75). Neonicotinoids (e.g., imidacloprid) and synthetic pyrethroids (e.g., cypermethrin) persist in floral tissues, exposing pollinators like bees to residues that impair foraging efficiency and reproduction (75). In soil ecosystems, beneficial fauna such as earthworms and microarthropods suffer toxicity, degrading soil structure and nutrient cycling (76). Additionally, pesticide runoff contaminates aquatic systems, where bioaccumulation in fish and amphibians disrupts food webs (77). These impacts underscore the imperative for sustainable practices like IPM and biological controls to mitigate non-target impacts and preserve biodiversity in cardamom agroecosystems (75).

Human health risks

The residual effects of pesticides in cardamom cultivation pose significant risks to human health, particularly for farmers, workers and consumers. These risks arise from direct exposure during pesticide application, consumption of contaminated cardamom and indirect exposure through contaminated water and soil.

Consumption of pesticide-contaminated cardamom poses grave health risks, as residues of organophosphates (e.g., chlorpyrifos) and neonicotinoids (e.g., imidacloprid) persist in capsules when applied excessively or near harvest, often exceeding (4). As demonstrated in study, such residues cause acute poisoning (e.g., nausea, vomiting) and chronic conditions like neurotoxicity, cancer and liver damage (4). A study specifically linked monocrotophos specifically linked monocrotophos residues in cardamom to severe health risks, reinforcing the urgency of mitigation strategies (34). To address these threats, adherence to PHIs, post-harvest processing and rigorous residue monitoring as advocated in are critical to safeguarding consumer health (4).

Mitigation strategies

Integrated pest management

To minimize the residual effects of pesticides in cardamom cultivation and ensure environmental and human safety, several mitigation strategies can be implemented. Table 3 illustrates the details on the IPM. These strategies primarily focus on reducing pesticide use, optimizing application practices and promoting sustainable farming methods.

Pesticide application practices

The amount of pesticide used in cardamom production varies depending to the environmental factors and pest pressure. Farmers often abide by advised pesticide usage rules, including dosage and time recommendations. However, adherence may fluctuate due to factors such as sudden pest outbreaks or unpredictable weather conditions. Multiple application techniques are employed in cardamom production, each with varying degrees of effectiveness and environmental impact.

Pesticide application practices

a. Foliar spraying: The most used method, where in pesticides are sprayed directly onto the leaves. This method is efficient for contact insecticides and fungicides.

b. Soil drenching: Involves applying directly to the soil around the plant base of the plant to control soil-borne pests and diseases.

c. Systemic application: Involves the use of systemic pesticides that are absorbed by the plant and provide internal protection against pests.

d. Aerial spraying: Used in larger plantations, this method involves spraying pesticides from aircraft to cover large areas quickly.

Frequency and timing of pesticide application

The frequency and timing of pesticide application in cardamom cultivation are critical factors that influence pest control efficacy, residue levels and environmental impact. Pesticides are typically applied based on pest life cycles, crop growth stages and environmental conditions.

a) Frequency of pesticide application in cardamom cultivation

Table 2. Pesticides residues that are harmful to beneficial insects

Non target organism	Exposure route	Effects	Example	Reference
Pollinators	Contaminated flower, pollen and nectar	Neurotoxicity, reproductive issues, mortality	Imidacloprid harming bees	(87)
Soil fauna	Direct contact, ingestion of soil	Toxicity, behavioural changes, population decline	Chlorpyrifos reducing earthworm populations	(88)
Aquatic life	Run off, leaching into water bodies	Acute toxicity, bioaccumulation, reproductive issues	Cypermethrin harming fish	(89)
Beneficial insects	Preying on pests, inhabiting treated areas	Mortality, behavioral changes, population decline	Synthetic pyrethroids harming predatory beetles	(90)
Birds and mammals	Contaminated food or water	Bioaccumulation, reproductive issues, mortality	DDT causing bird population decline	(91)

hinges on pest pressure, pesticide type and rainfall patterns. Contact pesticides require frequent reapplication compared to systemic pesticides with prolonged efficacy. Rainfall-induced wash-off necessitates additional treatments (e.g., chlorpyrifos applied every 15-20 days during peak infestations balancing pest control and environmental/health risks (13).

b) Timing: Pesticide timing aligns with growth stages: vegetative (thrips/borers), flowering (capsule borers) and post-harvest (soil pests) (13). Imidacloprid targets aphids/thrips during early flowering (13), while environmental strategies (e.g., avoiding pre-rain sprays, cooler-hour applications) reduce runoff (13). Such precision ensures sustainable pest management and minimal ecological disruption.

Regulatory frameworks and Good agricultural practices (GAP)

Ensuring safe pesticide use and minimize residues in cardamom cultivation, robust regulatory frameworks and mitigation strategies are essential. Regulatory authorities establish pesticide-specific based on risk assessments to safeguard consumers. Adopting Good agricultural practices (GAP)-including precise application timing, dosage and methods-reduces excessive pesticide use while maintaining efficacy.

IPM and holistic Impact of mitigation measures

Utilization of biological controls (e.g., beneficial insects), cultural practices and bio-pesticides (Table 4), offer sustainable alternatives to chemical pesticides, lowering residue risks. These measures collectively protect consumer health, preserve ecosystems and promote sustainable farming by balancing pest control with environmental stewardship.

Conclusion

While the use of toxic pesticides is vital for pest control in cardamom farming, it also poses health and environmental risks. A comprehensive understanding of pesticide usage patterns-including the types of chemicals used, application method, frequency and environmental drivers-is crucial for guiding's mitigation strategies. Achieving a balance between crop protection and environmental sustainability requires research, education and policy reforms. Promoting safer alternatives (e.g., biopesticides) and farmer awareness reduces chemical reliance and residues. A collaborative effort ensures eco-friendly practices, safeguarding ecosystems and public health without compromising yields.

Future prospective

Future research should prioritize mechanistic studies to identify microbial consortia (e.g., *Pseudomonas*, *Bacillus*) and enzymatic pathways (e.g., hydrolases) governing pesticide degradation in cardamom rhizospheres, alongside plant-specific metabolic traits (e.g., cytochrome P450 activity) influencing species-specific dissipation rates. These efforts must be complemented by advanced analytical tools, such as CRISPR-based biosensors and machine learning models, to enable real-time residue detection and predictive mapping of pesticide persistence under varying agroclimatic conditions. Sustainable mitigation strategies, including nano-encapsulated biopesticides and biochar-microbe remediation, should be tested to reduce chemical reliance, while climate-resilient approaches (e.g., hydrogel-based slow-release formulations) address warming-induced leaching risks. Concurrently, socio-economic interventions, like participatory farmer trials and policy reforms for cardamom-specific MRLs, can bridge lab-to-field gaps,

Table 3. Integrated Pest Management (IPM) (92)

Component	Description	Examples/Strategies
Biological control	Use of natural predators, parasites, or pathogens to control pest populations.	√ Release of ladybugs to control aphids. √ Use of Trichogramma wasps for capsule borers.
Cultural practices	Modifying farming practices to reduce pest habitats and reproduction.	√ Crop rotation with non-host crops. √ Intercropping with pest-repellent plants like marigold.
Mechanical control	Physical methods to remove or block pests.	√ Use of traps for thrips and borers. √ Barriers to prevent pest entry.
Chemical control	Judicious use of pesticides as a last resort.	√ Use of selective pesticides with low toxicity to non-target organisms. √ Adherence to pre-harvest intervals (PHIs).
Monitoring and scouting	Regular field inspections to detect pest populations early.	√ Use of pheromone traps to monitor pest levels. √ Visual scouting for pest damage.
Resistant varieties	Cultivation of cardamom varieties resistant to pests and diseases.	√ Planting high-yielding, pest-resistant varieties.
Sanitation	Maintaining field hygiene to reduce pest breeding sites.	√ Removal of infected plant debris. √ Proper disposal of crop residues.

Table 4. Alternative to chemical pesticides

Alternative	Description	Benefits	Example	Reference
Organic farming	Avoids synthetic inputs, focuses on natural methods	Reduces residues, improves soil health	Organic cardamom cultivation in Kerala	(12)
Biopesticides	Derived from natural sources like plants, bacteria, or fungi	Eco-friendly, low toxicity, biodegradable	Neem-based biopesticides for thrips control	(93)

while genomic innovations (CRISPR-edited microbes, omics-driven insights) and post-harvest technologies (ozone treatment, block chain traceability) ensure consumer safety and global trade compliance. Together, these interdisciplinary strategies offer a roadmap to balance productivity, ecological health and socio-economic equity in cardamom cultivation.

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Authors' contributions

The first draft of the manuscript was written by PS and all authors commented on previous versions of the manuscript. SS, VR, KV, GA and SR reviewedthe manuscript with valuable inputs. All authors contributed to study conception and design. All authors read and approved the final manuscript.

Compliance with ethical standards

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