SATSA Mukhapatra - Annual Technical Issue **30** : 2026 ISSN 0971-975X

Science-Based Pesticide Residue Management for Food Safety : From Field to Compliance in West Bengal's Tea and GI-Tagged Crops

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(Received : December 05, 2025; Revised : January 12, 2026; Accepted : January 14, 2026)

ABSTRACT

Toxic pesticide residue management is central to ensuring food safety, regulatory compliance, and export competitiveness, particularly for West Bengal's tea industry and its diverse portfolio of GI-tagged commodities. Although India is a low pesticide user globally, residue violations frequently arise from off-label chemical applications, inadequate understanding of PHI and pesticide half-life, and gaps between field realities and regulatory frameworks. The science-based, integrated approach to residue mitigation—linking the roles of CIB&RC, FSSAI, and PPC regulations with Good Agricultural Practices (GAP), IPM adoption, and emerging field innovations. It highlights how PHI, degradation kinetics, and MRL alignment underpin compliance, while dispelling common misconceptions related to pesticide safety, organic production, and residue detectability. Further, there is a need for cheap and rapid field-level detection tools, stronger surveillance systems, and targeted farmer capacity-building to reduce non-compliance. By harmonizing scientific understanding, regulatory discipline, and field-level stewardship, West Bengal's tea sector and other GI crops can enhance food safety, protect ecological integrity, and strengthen their position in domestic and export markets.

Keywords: Pesticide residue, MRL, Food safety, Compliance, PHI, Regulatory framework.

Introduction

Agriculture today stands at a complex intersection of productivity, safety, and sustainability. Pesticides—among the most widely used crop protection tools—play an indispensable role in preventing yield losses caused by insects, pathogens, and weeds. Global estimates suggest that without chemical and biological plant protection, crop losses could exceed 40% for major commodities such as cereals, fruits, and vegetables (Oerke, 2006). Yet, the same pesticides that safeguard food production also raise legitimate concerns regarding environmental contamination, human health effects, and market compliance when misused.

Public perception often assumes that India is among the highest pesticide users globally; however, empirical data strongly

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contradicts this narrative. According to FAO STAT (2023), India's average pesticide consumption is approximately 0.45 kg active ingredient per hectare, which is significantly lower than that of many developed and emerging agricultural economies. For example, Brazil exceeds 10 kg/ha, while the United States, Canada, Australia, and China typically record 2–3 kg/ha or more (Figure 1). India does not even feature among the top 10 pesticide-consuming nations on a per-hectare basis—a fact that underscores the importance of shifting the discourse from fear-based assumptions to evidence-based understanding.

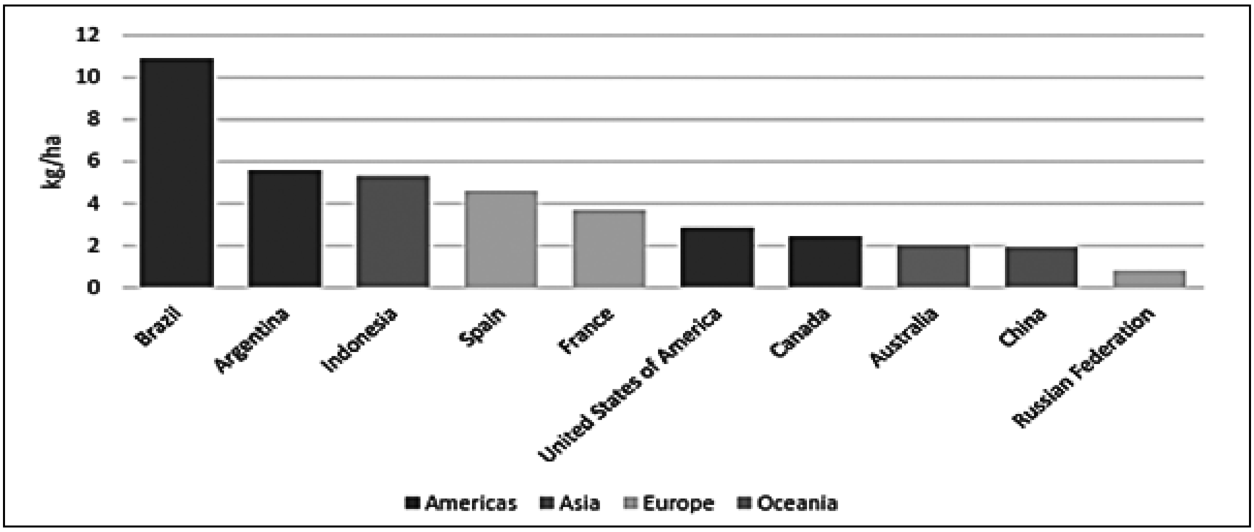

Figure 1. Average pesticide use rate (Kg/ ha). Source : FAO STAT (2023)

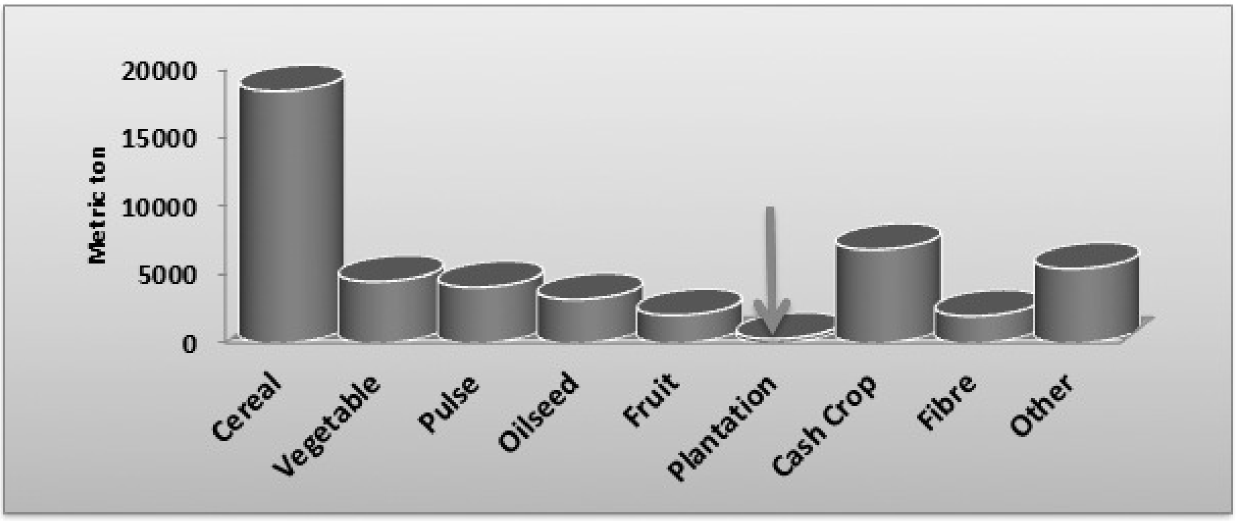

Figure 2. Commodity wise Pesticide use in 2022-23 in India. Source : Ministry of Agriculture & Farmers Welfare, Govt. of India

A similar misconception persists at the national level. Data from the Department of Agriculture, Cooperation and Farmers' Welfare, Government of India (DAC&FW, 2022) shows that states such as Maharashtra, Uttar Pradesh, Punjab, Andhra Pradesh, and Madhya Pradesh consume significantly higher total quantities of pesticides compared to West Bengal. Crop-wise consumption also reveals a clear pattern: cereals account for over 20,000 MT of annual pesticide use, followed by vegetables, pulses, oilseeds, and fruits. In comparison, plantation crops such as tea and coffee use a minuscule fraction of the national total (Figure 2), yet they face some of the highest rates of regulatory non-compliance (≈40%). This apparent contradiction arises not from high pesticide usage, but from stringent regulatory frameworks, intensive surveillance, and frequent detections of off-label or unapproved chemical applications (Bhat *et al.*, 2018; Kole *et al.*, 2020).

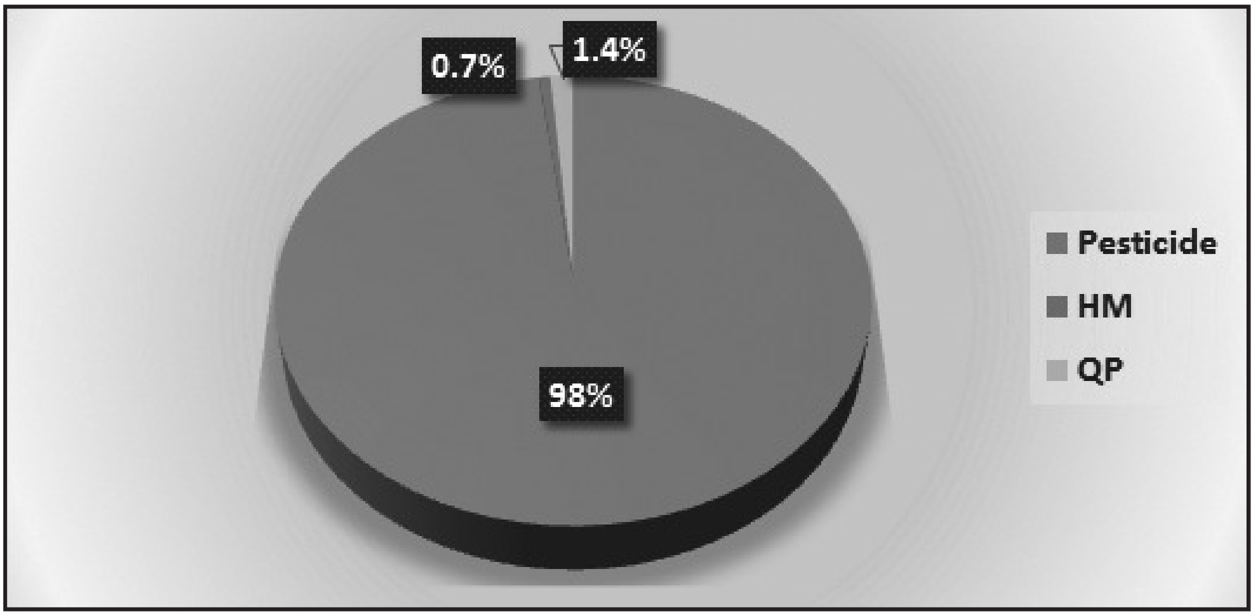

Figure 3. Reason of Non-conformance (2024) in Tea

In India, the Food Safety and Standards Authority of India (FSSAI) serves as the apex regulator governing contaminants and food safety parameters under the Food Safety and Standards (Contaminants, Toxins and Residues) Regulations, 2011. As per FSSAI 2025, FSSAI currently oversees more than 500 food categories, covering pesticide residues, heavy metals, biochemical parameters, and naturally occurring toxins (NOTs). Within this framework, tea—one of India's most widely consumed beverages and a major export commodity—often registers non-compliance due not only to pesticide residues exceeding Maximum Residue Limits (MRLs) but also to excess heavy metals, off-label pesticide usage, and biochemical issues such as crude fibre content. Among these, pesticide residue violations remain the single largest contributor in tea (Figure 3).

In West Bengal—home to globally valued tea-producing regions such as Darjeeling, Dooars, and Terai—the challenges of residue management are further amplified by the expectations of international markets. Export destinations including the European Union, UK, Iran and the United States maintain some of the strictest MRL standards in the world (Table 1). Non-compliance leads to export consignment rejection, economic loss, and erosion of brand reputation, especially for origin-linked products such as Darjeeling Tea, which commands premium status due to its Geographical Indication (GI) protection.

Beyond tea, West Bengal hosts a diverse portfolio of GI-tagged commodities such as *Lakshmanbhog*, *Fazli*, and *Himsagar* mangoes, *Tulaipanji* and *Gobindobhog* aromatic rice; queen pineapples; and a wide array of floriculture products and aquaculture species. These crops hold significant export promise but equally depend on rigorous pesticide residue compliance and traceability frameworks. For these sectors, residue management is not merely a regulatory formality—it is a catalyst for market access, consumer trust, and rural economic resilience.

Thus, effective pesticide residue management lies at the intersection of science-based regulation, responsible stewardship, and sustainable agricultural practices. Strengthening analytical surveillance, improving adherence to Good Agricultural Practices (GAP), discouraging off-label usage, and leveraging rapid technologies such as AI-enabled field detection tools (e.g., ACLIVIA : Figure 4) can collectively transform West Bengal's tea and GI-crop sectors. By rooting policy and practice in verified data—rather than perception—India's agricultural systems can advance toward a future defined by food safety, export competitiveness, and environmental sustainability.

Scientific Foundations: Residue Chemistry and Detection

Pesticide residues refer to the trace quantities of active substances, metabolites, or degradation products that remain in or on agricultural commodities after the application of plant protection chemicals. The toxicological significance of a residue depends not on its mere detectability but on its concentration, chemical properties, persistence (DT_{50}), bioaccumulation potential, and exposure duration. Modern food safety regulations therefore rely on scientifically derived metrics—such as Maximum Residue Limits (MRLs), Acceptable Daily Intake (ADI), Acute Reference Dose (ARfD), and NOAEL (No Observed Adverse Effect Level) values—to evaluate consumer risk. These thresholds are set by bodies such as FSSAI, Codex Alimentarius, EFSA, EPA (USA), and MAFF (Japan) based on long-term toxicological studies, dietary exposure modelling, and uncertainty/safety factors.

From an analytical perspective, pesticide residue detection has evolved dramatically in the past two decades. Earlier methods such as gas-liquid chromatography or thin-layer chromatography have been replaced by high-resolution, multi-residue chromatographic techniques capable of detecting hundreds of analytes at sub-ppb (parts per billion) levels. Today, instruments such as GC-MS/MS, LC-MS/MS, UHPLC-

Orbitrap HRMS, and ICP-MS for metals are central to food residue laboratories worldwide (Gkountouras *et al.*, 2024). These are highly sensitive and reliable but require sophisticated infrastructure, skilled personnel, and considerable time for analysis. These limitations make them less practical for on-site testing and rapid decision-making, particularly in resource-constrained settings (Mukherjee *et al.,* 2025).

To bridge the gap between laboratory-based residue analysis and field-level decision-making, rapid pesticide detection kits have gained prominence as practical, low-infrastructure screening tools (Kakkar *et al.*, 2024; Kinyua *et al.*, 2025). These platforms employ immunoassays, colorimetric reactions, and biosensor-based principles to deliver qualitative or semi-quantitative results within minutes, enabling early identification of potential residue risks before harvest or dispatch (Jara *et al.*, 2022). Among current innovations, ACLIVIA stands out as an AI-enabled, field-deployable system validated for detecting key high-risk pesticides—monocrotophos, acephate, acetamiprid, imidacloprid, dinotefuran, and fipronil—at 10 ppb levels in green tea leaves. Complementary technologies include BARC's biosensor-based Biokit for organophosphate and carbamate detection (BARC, 2019), the Defence Food Research Laboratory (DFRL) on-site Pesticide Detection Kit (DRDO, 2019), and the NIFTEM-K rapid test system, supported by Tata Consumer Products Ltd., which screens for major pesticide groups in tea within 30–60 minutes (Admin, 2024). Collectively, these tools strengthen decentralized surveillance and support timely corrective actions in residue management.

A transformative development in pesticide residue chemistry is the introduction of the QuEChERS method (Quick, Easy, Cheap, Effective, Rugged, and Safe), first developed by Anastassiades *et al.*, 2003. QuEChERS is now the most widely adopted sample preparation method globally, endorsed by AOAC International and European Norm (EN) for multi-residue pesticide testing in fruits, vegetables, cereals, spices, and beverages—including tea.

Figure 4. ACLIVIA, an AI-based rapid screening platform for detecting pesticide residues in green tea leaves.

Recent surveillance data indicate that a small group of unapproved or banned pesticides—particularly acetamiprid, imidacloprid, monocrotophos, acephate, dinotefuran, cypermethrin, and fipronil—accounts for nearly 90% of pesticide residue non-compliance in tea under FSSAI's default MRL of 10 ppb. Because these molecules lack crop-specific GAP and PHI data, even trace residues frequently exceed the stringent default limit, making them high-risk chemistries for the tea sector. In this context, ACLIVIA, an AI-enabled rapid detection platform, plays a pivotal role by enabling on-field screening and early identification of these high-risk residues at the farm-gate level, thereby supporting evidence-based decision-making (Mukherjee *et al.*, 2025). In addition to these unapproved molecules, several approved pesticides—such as lambda-cyhalothrin, carbendazim, mancozeb, fenazaquin, fenpyroxymate, bifenthrin, thiamethoxam, thiacloprid, clothianidin, propargite, and flubendiamide—are also frequently detected in tea, underscoring the need for strengthened PHI adherence and robust analytical surveillance.

Regulatory Landscape

India's pesticide governance framework is shaped by two apex regulatory bodies operating at complementary levels: the Central Insecticides Board & Registration Committee (CIB&RC) and the Food Safety and Standards Authority of India (FSSAI). Together, they determine which pesticides may be used in agriculture and what residue levels are permissible in food.

The CIB&RC, established under the Insecticides Act, 1968, is the national authority for registering pesticide molecules and formulations after evaluating toxicology, environmental fate, residue behavior, efficacy, and Good Agricultural Practices (GAP). As per the latest list published up to 30th October 2025 (PPQS/ CIB&RC, 2025), India has 368 registered pesticide molecules and 1,044 registered formulations, with additional chemistries being approved periodically for specific crops and uses.

Complementing this, the FSSAI is the apex body for setting Maximum Residue Limits (MRLs) and monitoring food safety across both domestic and imported commodities under the Food Safety and Standards Act, 2006. Through its surveillance systems and designated laboratories, FSSAI enforces MRL compliance, heavy metal limits, and other food quality parameters across 500+ food categories, including tea.

In the tea sector, crop-specific regulation is provided by the Plant Protection Code (PPC) of Tea Board India. Under PPC Version 18.0, only 48 pesticide molecules and 62 formulations (PPF) are approved for use in tea (Figure 5). Similar restrictions exist for other high-value crops, where a limited number of registered chemistries often do not fully address field-level pest pressures.

This regulatory gap—where farmers face severe pest outbreaks but have access to only a narrow list of approved molecules—frequently drives the off-label or unapproved use of other pesticides. Since GAP and PHI (pre-harvest intervals) are not established for these unapproved pesticide–crop combinations, they carry a high risk of MRL exceedance, contributing significantly to India's non-compliance trends in tea and other specialty crops.

The challenge becomes more acute in global trade. Export destinations such as the EU, UK and the USA impose extremely stringent MRLs—often far lower than Codex—and maintain rigorous border surveillance. Even trace residues from off-label applications can lead to rejections, alerts, and market disruptions, making alignment with CIB&RC-approved chemistries and PPC guidelines essential for sustaining export competitiveness.

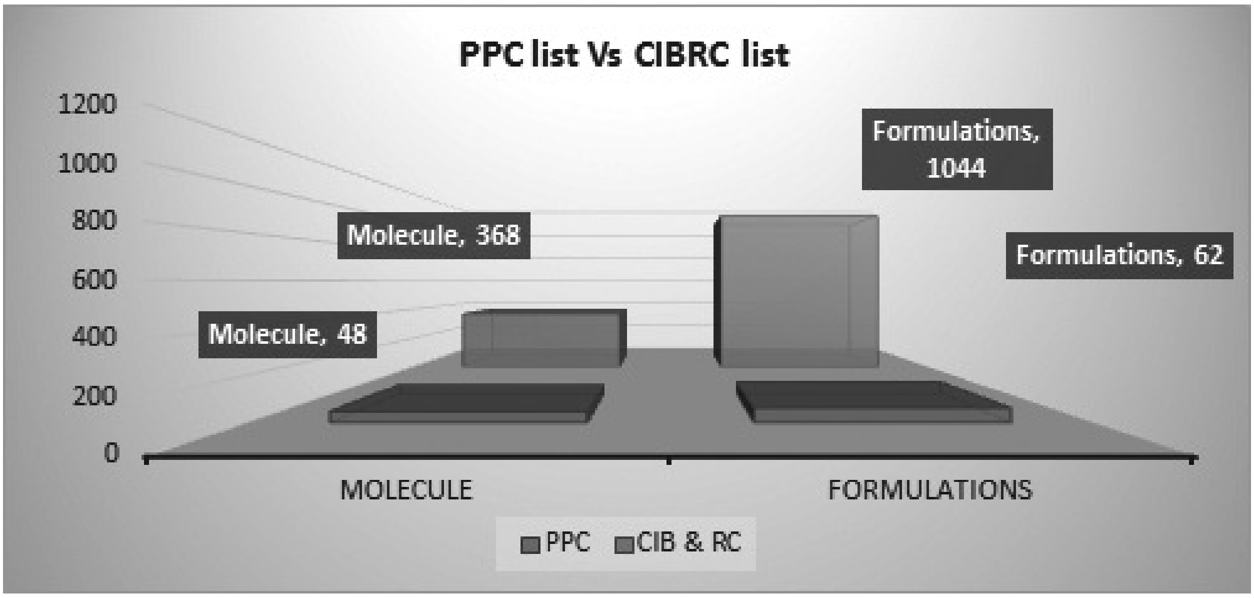

Figure 5. Comparison between PPC V 18.0 & CIB &RC listed chemicals and formulations.

Field Practices : Integrated Pest Management and Innovations

Integrated Pest Management (IPM) in tea and other GI-linked crops relies on a balanced combination of biological agents, cultural practices, mechanical tools, and judicious chemical use. However, the effectiveness of chemical interventions—and ultimately residue compliance—depends fundamentally on understanding Pre-Harvest Interval (PHI) and pesticide half-life (DT_{50}).

PHI is the minimum time required between pesticide application and harvest to allow residues to degrade to levels that comply with the Maximum Residue Limit (MRL) (Figure 6). PHIs are scientifically established only for approved (label-claimed) pesticides for the specific crop, based on supervised field trials under Good Agricultural Practices (GAP). As a result, PHIs differ across commodities: typically 3 days for leafy vegetables, 5 days for fruits, and 7 days for tea. Harvesting before completion of PHI often results in residue levels above the MRL, leading to non-compliance.

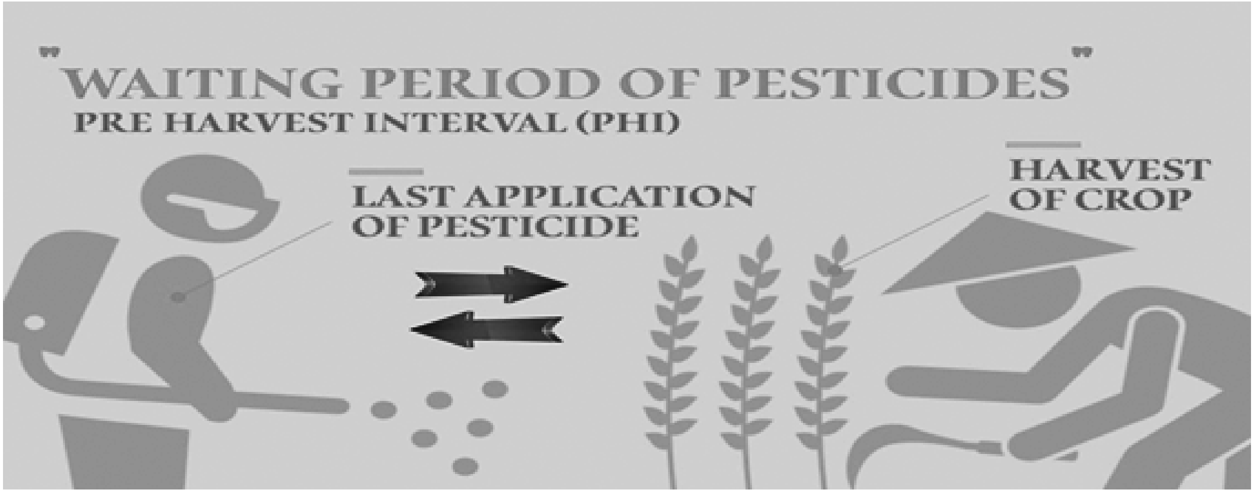

Figure 6. Pre Harvest Interval (PHI) or waiting period

The situation becomes more complex for off-label or unapproved pesticides, where no crop-specific PHI exists and FSSAI assigns a default MRL of 10 ppb. Even if harvested after the general 7-day interval, many unapproved chemistries cannot degrade to such a stringent limit, resulting in unavoidable violations. In contrast, an approved pesticide with an MRL of 1 ppm can degrade below its regulatory limit within the established PHI. This difference underscores why field-level compliance is achievable only when using approved molecules and why off-label use remains the primary cause of MRL exceedances in tea or in any other crop like fruits and vegetables.

The pesticide half-life governs how quickly residues dissipate (Figure 7). Molecules with longer DT_{50} values require more time to decline within safe limits; for unapproved pesticides expected to reach 10 ppb, the required degradation period may extend well beyond practical plucking or harvesting cycles. Understanding this degradation behaviour is therefore essential for aligning pest control with residue compliance.

By integrating IPM with science-based PHI adherence, knowledge of degradation kinetics, and rapid field testing, growers can significantly reduce residue risks and strengthen compliance across tea and other GI-tagged commodities.

Myth-Busting

Public understanding of pesticides is often shaped by perception rather than evidence. A common belief is that all pesticides are inherently dangerous; however, as with any chemical input, risk is determined by dose, application method, and adherence to Good Agricultural Practices (GAP). Registered pesticides undergo extensive toxicological evaluation before approval, and when used as per guidelines, they support crop protection without compromising food safety.

Another widely held myth is that organic farming guarantees residue-free produce. In reality, organic systems rely on natural pesticides such as azadirachtin,

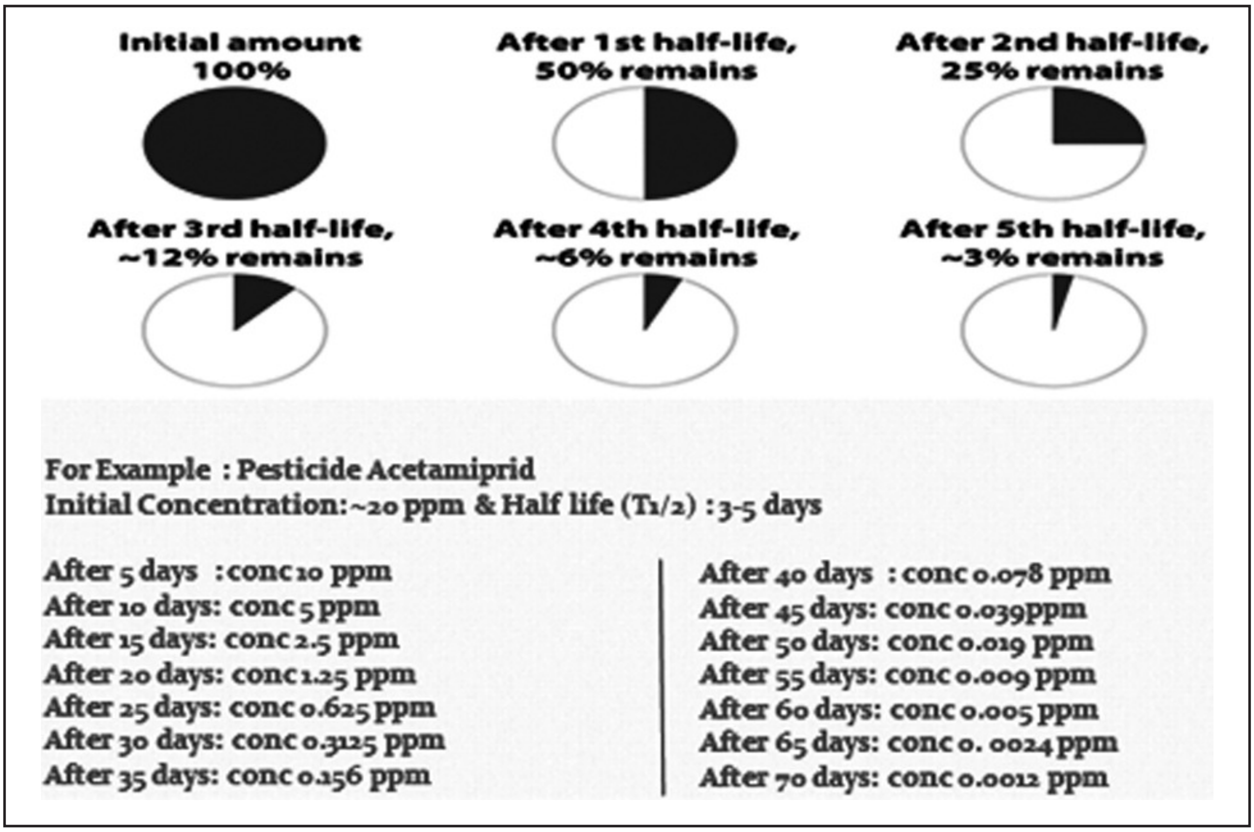

Figure 7. Pesticide Half-Life for dissipation in crop.

karanjin, and nicotine, which can also leave measurable residues. Cross-contamination from neighbouring fields, soil persistence, and environmental drift further demonstrate that “organic” does not automatically mean “zero residues.”

The assumption that any detectable residue is unsafe is also misleading. Modern analytical instruments can detect chemicals at parts-per-billion levels—far below concentrations that pose health risks. Food safety is governed by Maximum Residue Limits (MRLs), which incorporate large safety margins and are set well below harmful exposure levels. Therefore, residues below MRLs are scientifically validated as safe for consumption.

Ultimately, most residue-related concerns arise not from pesticide hazard itself but from overuse, including off-label application, formulation/dose of application, non-adherence to PHI, crop growth stage of application or use of unapproved molecules. By grounding decisions in science rather than perception—and by strengthening farmer training, GAP adoption, and rapid field testing—stakeholders can navigate the pesticide paradox effectively: protecting crops while ensuring food safety and regulatory compliance.

Conclusion

Strengthening pesticide residue management in tea and other GI-linked crops requires a coordinated, science-driven approach that integrates GAP, PHI adherence, understanding of pesticide half-life, and strict use of CIB&RC-approved chemistries. Aligning field practices with regulatory guidelines like PPC V18.0 and FSSAI regulatory limits is essential for ensuring that residues degrade to safe levels, reducing the risk of non-compliance and safeguarding domestic and export markets.

Scaling of rapid and cheap detection tools, expanding decentralized testing capacity, and improving surveillance will enable early identification of high-risk residues and timely corrective action. Equally important is clear, accessible communication to farmers and FPOs (Farmer Producer Organizations) on the risks of off-label pesticide use and the scientific basis of PHI and MRLs. Replacing perception-driven myths with evidence-based understanding remains central to improving compliance.

Looking ahead, sustained investment in research on degradation kinetics, pest dynamics under changing climate, and identification of safer molecules will support long-term sustainability. By combining science-based regulation, field-level innovation, and targeted capacity building, the agricultural sector can ensure production of safe, compliant, and globally competitive commodities while maintaining environmental and consumer trust.

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Table 1. Comparison of MRLs of a few pesticides in tea fixed by CODEX & other countries

Sl. No.	Pesticides	CODEX MRL	India (mg/kg) (mg/kg)	EU MRL (mg/kg)	USA (mg/kg)	Canada (mg/kg)	Australia (mg/kg)	Japan (mg/kg)	China (mg/Kg)	UK (mg/Kg)	Russia (mg/Kg)
1	2,4 D	-	0.05*	0.1*	-	-		-	-	0.1*	
2	Acetamiprid	-	0.01*	0.05*	50	-		30	-	0.05*	
3	Azoxystrobin	-	-	0.05*	20	20	20(T)	10	-	0.05*	
4	Bifenthrin	30	30	30	30	30	5	30	5	30	
5	Bitertanol	-	0.05*	0.05*	-	-		0.1	-	0.05*	
6	Boscalid	40	-	40	70	-	40	60	-	40	
7	Buprofezin	30 (Green)	-	0.05*	20	30		30	10	0.05*	
8	Carbendazim	-	0.5	0.1*	-	-		10	5	0.1*	
9	Carfentrazone Ethyl	-	0.02*	0.1*	0.1	-		0.1	-	0.02*	
10	Chlorantraniliprole	80	-	80	50	-	80	50	-	80	-
11	Chlorfenapyr	60	-	50	70	70	60	40	-	50	
12	Chlorpyrifos	-	2	0.01*	-	-	-	10	-	0.01*	2.0
13	Clothianidin	0.7	0.7	0.7 (0.05* from 07/03/2026)	70	70	0.7(T)	50	-	0.7	0.7*
14	Cyantraniliprole	50	-	50	30		-	30	-	50	-
15	Cyclaniliprole	50	-	0.05*	50	50	50	30	-	50	
16	Cyflumetofen	-	0.05*	0.05*	40	-		40	-	0.05*	
17	Cypermethrin	15	0.01*	0.5	15	-	0.5	20	20	0.5	20
18	Deltamethrin	5	5	5	-	7	5	10	10	5	5
19	Dicofol	40	40	20	50	-	5	3	0.2	20	20
20	Difenoconazole	20	-	0.05*	15	30	20	15	10	0.05*	
21	Diflubenzuron	40	-	0.05	0.5		0.1	20	20	0.05	-

Sl. No.	Pesticides	CODEX MRL	India (mg/kg) (mg/kg)	EU MRL (mg/kg)	USA (mg/kg)	Canada (mg/kg)	Australia (mg/kg)	Japan (mg/kg)	China (mg/Kg)	UK (mg/Kg)	Russia (mg/Kg)
22	Emamectin Benzoate	0.1	0.06	0.09	0.5	-	0.1	0.5	-	0.02*	
23	Endosulfan	10	-	30	-	-	10	30	10*	30	30
24	Ethion		-	5	3	-	-	5	0.3	-	3
25	Etoxazole	15	15	0.05*	15	15	15	15	-	15	
26	Fenazaquin	-	3	9	10			10	15	10	
27	Fenbuconazole	30	-	0.05*	30		30	-		0.05*	
28	Fenpropathrin	3	2	2	2	2	2	25	5	2	2
29	Fenpyroximate	8	6	8	20	44	0.1	40	8	8	
30	Flubendiamide	50	50	50	50	50	0.02	50	-	0.02*	
31	Flufenoxuron	20	-	15	-	-	20	15	-	15	
32	Fluvalinate	-	0.01*	0.05*	-	-		10	-	0.01*	
33	Glufosinate ammonium	-	0.01	0.1*	-	0.5	0.05*	0.3	0.5	0.1*	
34	Glyphosate	-	1	2	1	-	20(T)	1	1	2	
35	Hexaconazole	-	5	0.05*	-	-		-	-	0.05*	
36	Hexythiazox	15	15	15	15	15	4	15	15	4	
37	Imidacloprid	50	0.01*	0.05*	-	50	50	10	0.5	0.05*	
38	Indoxacarb	5	-	5	-	-	5	-	5	5	
39	L-cyhalothrin	-	0.05*	0.01*	-	2	1	15	15	0.01*	
40	Mancozeb	-	3	0.1*	-	-		-	-	0.1*	
41	Methidathion	-	-	0.1*	-	-		1	-	0.05*	0.5*
42	Methoxyfenozide	80	-	80	-	-	80	70	-	80	
43	Oxyfluorfen	-	0.2	0.05*	-	-		-	-	0.05*	
44	Paraquat	0.2	0.2	0.05*	-	-		0.3	-	0.05*	0.2*
45	Permethrin	20	-	0.1*	20	-	0.1	20	20	0.1*	20*

Sl. No.	Pesticides	CODEX MRL	India (mg/kg) (mg/kg)	EU MRL (mg/kg)	USA (mg/kg)	Canada (mg/kg)	Australia (mg/kg)	Japan (mg/kg)	China (mg/Kg)	UK (mg/Kg)	Russia (mg/Kg)
45	Permethrin	20	-	0.1*	20	-	0.1	20	20	0.1*	20*
46	Picoxystrobin	15	-	10	-		15	-	20	0.1	-
47	Propargite	5	10	10	10	-		5	-	10	5.0*
48	Propiconazole	-	6	0.05*	4	4		0.1	-	0.05*	
49	Pyraclostrobin	6	-	0.1*	-	-	7T	25	-	0.1*	
50	Quinalphos	-	0.7	0.05*	-	-		0.1	-	0.05*	
51	Spinetoram	70	-	0.1*	70	-	70	70	-	0.1*	
52	Spiromesifen	70	70	50	40	60	50	30	-	50	
53	Thiacloprid	-	5	0.05	-	-	10	30	-	10	
54	Thiamethoxam	20	20	20 (0.05* from 07/03/2026)	20	-	20	20	10	20	
55	Tolfenpyrad	30 (Green)	-	0.01	30	30		20	-	0.05*	
56	Zineb	-	0.1	0.01	-	-		-	-	0.2*	

* Indicates lower limit of analytical determination; (T) temporary.