

Integrated Review of Emamectin Benzoate EC: Physicochemical Properties, Bioefficacy, Residue Behaviour and Environmental Considerations

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Abstract: A semi-synthetic avermectin insecticide called emamectin benzoate is frequently used to control economically significant insect pests, especially lepidopteran larvae. Its agricultural importance originates from high insecticidal efficacy, translaminar activity and a particular neurophysiological method of action involving allosteric activation of glutamate-gated chloride channels. However, because emamectin benzoate's exposure profile is influenced by formulation, application pattern, crop shape, environmental compartment, and degradation pathway, its environmental and food safety relevance cannot be determined just by efficacy.

This review incorporates published data on emamectin benzoate's physicochemical properties, mode of action, and bioefficacy along with residue dissipation, analytical determination, metabolism, and environmental destiny. EC formulations, comparative dissipation in various crops, formulation-dependent half-lives, photodegradation products, soil and water behavior, and possible effects on non-target organisms are all given special consideration. Although dissipation rates vary depending on the crop, developmental stage, formulation, and environmental conditions, reported field studies often show a quick reduction of parent residues in numerous crop matrices.

Emamectin B1a and similar transformation products must be taken into account when determining residues for enforcement and dietary risk assessment, according to regulatory evaluations. Recent evidence also indicates that resistance to emamectin benzoate can arise through target-site and metabolic mechanisms, emphasizing the need to integrate residue management with resistance management.

Keywords: emamectin benzoate; emulsifiable concentrate; physicochemical properties; bioefficacy; residue dissipation; QuEChERS; LC-MS/MS; environmental fate; photodegradation; non-target organisms; resistance management; MRL.

I. INTRODUCTION

Agricultural intensification has increased the need for insecticides capable of providing reliable pest suppression at comparatively low application rates. However, the value of an insecticide is now evaluated through a broader framework that includes efficacy, residue persistence, dietary exposure, environmental fate, effects on beneficial organisms and the possibility of resistance development. Emamectin benzoate occupies an important position in this context because it combines high activity against several economically important pests with a mode of action that differs from many conventional neurotoxic insecticides [1–3].



The agricultural performance of emamectin benzoate is closely related to its ability to penetrate leaf tissue and remain biologically available to feeding larvae. Its principal target is the glutamate-gated chloride channel (GluCl), and IRAC classifies it in Group 6, the avermectin/milbemycin group of GluCl allosteric modulators [6]. Activation of these channels increases chloride conductance and disrupts neuronal signalling, resulting in rapid feeding cessation, paralysis and eventual death.

Residue behaviour is equally important. Published field studies have reported relatively short dissipation half-lives in several crops, but the magnitude of dissipation differs among matrices and formulations. For example, Wang et al. reported half-lives of 1.34–1.72 days in cabbage, 2.75–3.09 days in apple and 1.89–4.89 days in soil [11]. Deng et al. reported half-lives of 0.8–2.8 days in rice plants and 1.9–3.8 days in soil [12]. More importantly for the present review, Wang et al. demonstrated that EC and microemulsion formulations could show different dissipation patterns in tender and mature cowpea [13]. Such observations demonstrate why a formulation-specific assessment is preferable to a single universal half-life.

Therefore, the goal of this review is to integrate four interrelated aspects of emamectin benzoate EC: (i) formulation behavior and physicochemical properties; (ii) bioefficacy and mode of action; (iii) residue behavior, dissipation kinetics, and analytical determination; and (iv) ecological considerations and environmental fate. Additionally, the study points out research gaps that can direct future efforts, especially in integrated environmental assessment and crop-specific residue investigations.

Figure 1. Integrated conceptual framework linking emamectin benzoate EC properties, efficacy, residues and environmental fate.

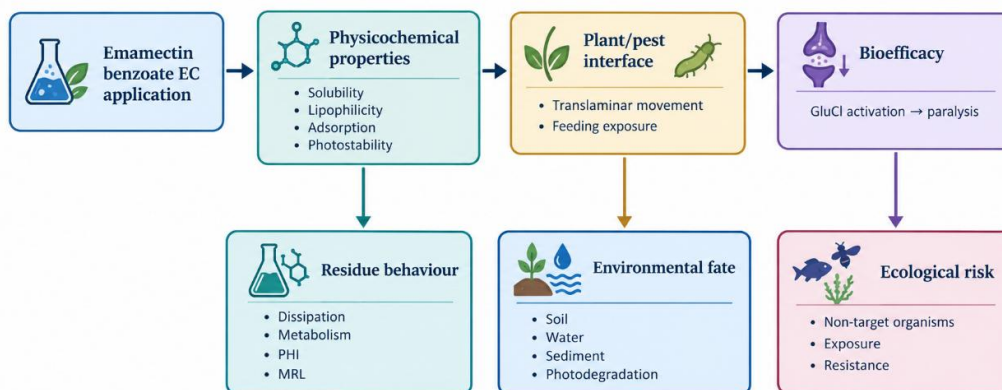


Figure 1. Integrated conceptual framework linking emamectin benzoate properties, efficacy, residue behaviour and environmental fate.

II. CHEMICAL IDENTITY, COMPOSITION AND PHYSICOCHEMICAL PROPERTIES

Emamectin benzoate is a macrocyclic lactone insecticide that is a member of the avermectin family. Emamectin benzoate, which has the chemical formula $C_{56}H_{81}NO_{15}$ and a molecular weight of about $1008.2 \text{ g mol}^{-1}$, is listed in PubChem as the primary salt representation [17]. Emamectin B1a benzoate predominates in commercial material, while B1b benzoate is present in lower amounts. When talking about residue definitions, molecular-weight-based computations, and analytical standards, this mixture should be specifically mentioned.

The compound's unique physicochemical behavior is attributed to its massive macrocyclic structure, several oxygen-containing functional groups, and tertiary amino functionality. The molecule's functional groups offer chances for hydrogen bonding and interactions with soil organic materials, and it is sufficiently lipophilic to attach to biological membranes and plant surfaces. As a result, it is not appropriate to interpret adsorption, photochemical modification, and biological availability from a single physicochemical measure since these processes can happen concurrently.

The distinction between the inherent qualities of the active ingredient and those of the manufactured product is crucial in an EC-focused assessment. The active agent, solvents, emulsifiers, and other formulation ingredients are all present



in an emulsifiable concentrate. These substances can change initial deposition, spreading, penetration, and droplet behavior, but unless proven experimentally, it is not reasonable to believe that they will change intrinsic toxicological or environmental qualities. Formulation can affect observed dissipation kinetics, as demonstrated directly by the cowpea comparison between EC and ME formulations [13].

Emamectin benzoate is also sensitive to photochemical transformation. Regulatory metabolism assessments have identified several photo-metabolites, including 8,9-Z-MAB1a, FAB1a, MFB1a and AB1a. In leafy crops, these products can collectively represent a meaningful fraction of total radioactive residues even when each individual metabolite is present at a relatively low proportion [18,19]. Thus, the apparent rapid decline of parent emamectin does not necessarily mean immediate disappearance of all emamectin-related residues.

Table 1. Selected physicochemical and regulatory characteristics of emamectin benzoate

Parameter	Summary	Relevance to review
Chemical class	Semi-synthetic avermectin / macrocyclic lactone	Determines neurotoxic mode of action and environmental behaviour
Principal components	B1a predominant; B1b minor	Important for analytical and residue definitions
Molecular formula (representative PubChem entry)	C ₅₆ H ₈₁ NO ₁₅	Useful for identity and analytical calculations
Molecular weight	~1008.2 g mol ⁻¹	Interpret carefully for mixture/salt representation
Mode-of-action group	IRAC Group 6	GluCl allosteric modulation
Key environmental processes	Photodegradation, adsorption, plant metabolism, transformation	Explain dissipation and compartmental exposure
Formulation focus	EC = active ingredient + formulation auxiliaries	Formulation may affect deposition and dissipation
Residue definition	Regulatory definitions focus on emamectin B1a and selected metabolites depending on purpose	Important for MRL and dietary risk interpretation
ADI / ARfD	JMPR 2023: ADI 0–0.0005 mg/kg bw; ARfD 0.02 mg/kg bw	Use current regulatory source rather than secondary summaries

III. MODE OF ACTION AND BIOEFFICACY

The distinctive insecticidal activity of emamectin benzoate is associated primarily with allosteric activation of glutamate-gated chloride channels. IRAC Group 6 describes these compounds as GluCl allosteric modulators that increase inhibitory chloride conductance and cause paralysis [6]. The high sensitivity of insects to this pathway explains the strong potency of emamectin benzoate at comparatively low use rates.



Figure 2. Simplified mode-of-action pathway of emamectin benzoate

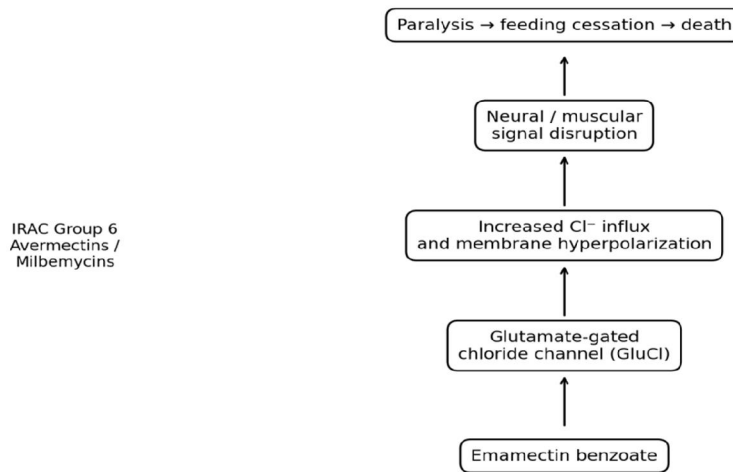


Figure 2. Simplified mode-of-action pathway of emamectin benzoate.

The substance is used to combat pests like *Helicoverpa*, *Spodoptera*, and *Plutella* species, and it works especially well against larval *Lepidoptera*. While more recent studies continue to record activity in many agricultural systems, early field study showed significant control of *H. armigera* and other pests [2,20–23]. However, pest species, developmental stage, application rate, coverage, environmental factors, and local population vulnerability all affect the level of control. The translaminar behaviour of emamectin benzoate is agronomically important. Following foliar application, the active ingredient can penetrate leaf tissue, creating exposure to feeding larvae that may not be directly contacted by the spray. Delivery-system research has attempted to improve deposition, photostability and biological performance, demonstrating that formulation science can modify how the active ingredient is presented to the target pest [24,25].

Table 2. Representative evidence on bioefficacy and resistance

Target / system	Evidence	Interpretation
<i>Helicoverpa armigera</i>	Early field studies reported >90% suppression under selected cotton-field conditions	Strong residual and ingestion activity; performance is pest- and rate-dependent
<i>Spodoptera</i> spp.	Activity demonstrated in laboratory and field systems	Larval stage and exposure route influence response
<i>Plutella xylostella</i>	Field-derived population reported >150-fold resistance in one study	Resistance can substantially reduce field performance
<i>Spodoptera litura</i>	CYP9A25 F116I mutation associated with resistance	Target/metabolic genetic mechanisms deserve monitoring
<i>Pieris rapae</i>	P450/GST-related detoxification associated with resistance phenotype	Metabolic resistance may complicate management
<i>Phenacoccus solenopsis</i>	Laboratory selection produced high resistance after repeated generations	Repeated selection can rapidly change susceptibility
<i>Spodoptera frugiperda</i>	GluCl knockdown reduced EB susceptibility	Supports GluCl as a functional target
Delivery systems	Nano/colloidal formulations can alter deposition and photostability	Formulation science may influence efficacy and persistence



IV. RESIDUE BEHAVIOUR AND DISSIPATION

Residue behaviour is one of the most important dimensions of emamectin benzoate use because the active ingredient is frequently applied to food crops. Residue studies generally evaluate initial deposition, dissipation kinetics, terminal residues at specified pre-harvest intervals (PHIs), and dietary risk relative to applicable MRLs. The interpretation of results requires attention to crop matrix, application rate, number of applications, formulation, climatic conditions and analytical sensitivity.

A recurring pattern across field studies is rapid dissipation of parent emamectin benzoate from many crop matrices. Wang et al. reported half-lives of 1.34–1.72 days in cabbage and 2.75–3.09 days in apple, compared with 1.89–4.89 days in soil [11]. Deng et al. reported 0.8–2.8 days in rice plants and 1.9–3.8 days in soil [12]. Such results support relatively rapid decline under the particular conditions studied, but they should not be converted into a universal half-life for all crops or formulations.

Formulation and crop maturity can materially affect dissipation. In cowpea, the half-life of EC was 1.34–1.39 days in tender pods and 1.74–2.31 days in old pods; for the ME formulation, corresponding ranges were 1.39–1.51 and 2.08–2.67 days [13]. This study is especially relevant to an EC-focused review because it demonstrates experimentally that formulation and harvest stage can change residue persistence.

Residue behaviour has also been studied in mango, cabbage, brinjal and cauliflower. A modified QuEChERS-HPLC-MS/MS method for mango showed acceptable recoveries and was used to determine field dissipation and terminal residues [27]. A multi-region cabbage study reported residues below the stated Chinese MRL at the recommended 7-day PHI and estimated chronic and acute risk quotients below 100% under the study assumptions [28]. A 2024 study of a tolfenpyrad + emamectin benzoate combination formulation in brinjal and cauliflower further illustrates the continuing importance of validated LC-MS/MS approaches for combination products [29].

An important conceptual issue is that decline of parent emamectin does not necessarily represent complete chemical disappearance. Plant metabolism and photodegradation can produce several related compounds. EFSA assessments identified 8,9-Z-MAB1a, FAB1a, MFB1a and AB1a among photo-metabolites, with their combined contribution to total radioactive residues reaching significant levels in some crop studies [18,19]. Consequently, risk assessment and regulatory residue definitions need to consider toxicologically relevant transformation products rather than relying solely on parent-compound measurements.

Processing may also alter residue composition. Regulatory assessments have reported degradation under standard hydrolysis conditions and have distinguished enforcement residue definitions from broader risk-assessment definitions [18,19]. For a review article, this distinction is valuable because it explains why the number reported by an analytical laboratory may not always correspond exactly to the residue definition used by a regulatory authority.

The standard first-order model used in many field studies can be expressed as $C_t = C_0 e^{-kt}$, with half-life $t_{1/2} = 0.693/k$. The model is useful for comparing studies but should be applied cautiously where biphasic decline, changing environmental conditions, repeated applications or metabolite formation are important. Environmental studies on foliage and decomposing leaves have demonstrated biphasic dissipation under some conditions, reinforcing the need to distinguish simple crop-surface decline from longer-term environmental fate [30].

Table 3. Representative residue and dissipation studies

Matrix / crop	Formulation / method	Reported behaviour	Reference
Cabbage	Field application; QuEChERS + LC-ESI-MS/MS	Half-life 1.34–1.72 d; LOQ 0.001 mg/kg	Wang et al., 2012 [11]
Apple	Field application; QuEChERS + LC-ESI-MS/MS	Half-life 2.75–3.09 d	Wang et al., 2012 [11]
Soil	Field application; QuEChERS + LC-ESI-	Half-life 1.89–4.89 d	Wang et al., 2012 [11]



	MS/MS		
Rice plant / soil	UPLC-MS/MS	Half-life 0.8–2.8 d in plants; 1.9–3.8 d in soil	Deng et al., 2020 [12]
Tender cowpea	EC	Half-life 1.34–1.39 d	Wang et al., 2021 [13]
Old cowpea	EC	Half-life 1.74–2.31 d	Wang et al., 2021 [13]
Tender cowpea	ME	Half-life 1.39–1.51 d	Wang et al., 2021 [13]
Old cowpea	ME	Half-life 2.08–2.67 d	Wang et al., 2021 [13]
Mango	Modified QuEChERS + HPLC-MS/MS	Field dissipation and terminal residues assessed	Bian et al., 2020 [27]
Cabbage, 12 regions	Modified QuEChERS + HPLC-MS/MS	Residues <0.01 mg/kg at 7 d in study conditions	Zhao et al., 2023 [28]
Brinjal / cauliflower	LC-MS/MS; combination formulation	Dissipation and dietary risk assessed	Sharma et al., 2024 [29]
Agricultural soil / surface water	HPLC-UV monitoring	EB1 detected in 97% of sampled soils in one Thai survey	2025 field monitoring [14]
Eggplant	Modified QuEChERS + HPLC-MS/MS	Multi-location field trial including metabolites	Pei et al., 2026 [31]

V. ANALYTICAL DETERMINATION OF EMAMECTIN BENZOATE RESIDUES

Reliable residue assessment depends on analytical methods capable of detecting emamectin at concentrations well below regulatory limits. QuEChERS followed by liquid chromatography coupled to tandem mass spectrometry has become a prominent approach because the analyte is relatively polar compared with many conventional hydrophobic pesticides while still requiring careful matrix cleanup. Wang et al. established an LC-ESI-MS/MS method with QuEChERS and reported an LOQ of 0.001 mg/kg in cabbage, apple and soil [11]. Deng et al. subsequently used UPLC-MS/MS for rice, plant, soil and field-water matrices [12].

Recent methods have extended the analytical scope to multiple pesticides and metabolites. Zhao et al. developed a modified QuEChERS-HPLC-MS/MS method for emamectin benzoate and imidacloprid plus imidacloprid metabolites in cabbage [28]. Pei et al. reported a modified QuEChERS-HPLC-MS/MS method for emamectin benzoate, spinetoram and major metabolites in eggplant field samples [31]. These developments are important because future residue assessment is increasingly moving from single-analyte monitoring toward multi-residue and metabolite-aware approaches.

Earlier immunochemical work also demonstrated that ELISA could provide sensitive screening of emamectin residues in agricultural products and showed cross-reactivity with several related metabolites [32]. Such approaches may have value for rapid screening, although confirmatory LC-MS/MS remains preferable when regulatory identification and quantification are required.

Quality parameters that should be reported in residue studies include calibration range, linearity, recovery, precision, LOQ, matrix effects, identification criteria and stability. A review should avoid comparing numerical residue values from studies with substantially different analytical sensitivity without noting the corresponding LOQs. 'Not detected' and '<LOQ' are analytical statements rather than proof of absolute absence.



VI. ENVIRONMENTAL FATE AND ENVIRONMENTAL CONSIDERATIONS

Figure 3. Conceptual environmental fate and exposure pathway

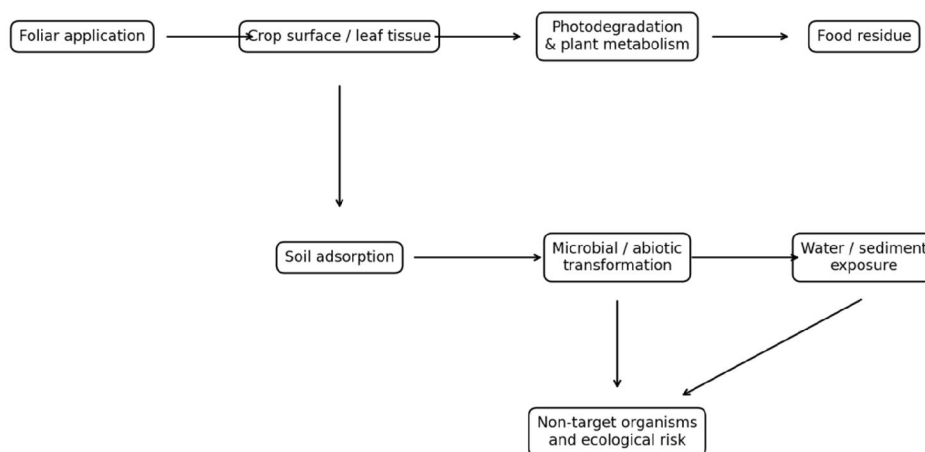


Figure 3. Conceptual environmental fate and exposure pathway of emamectin benzoate.

Table 4. Environmental fate and ecological considerations

Compartment / endpoint	Evidence	Implication
Crop surface	Extensive photodegradation and formation of several photo-metabolites	Parent decline should not be equated with disappearance of all residues
Soil	Adsorption and upper-soil retention reported; field persistence varies	Mobility and persistence are site-dependent
Surface water	Detectable residues possible after agricultural application	Runoff/drift should be considered
Marine sediment	Transformation to desmethyl emamectin reported	Metabolites may require environmental monitoring
Beneficial insects	Short-term foliar contact toxicity documented	Application timing and exposure reduction are important
Rove beetle predator	Lethal/sublethal effects reported	Non-target predator conservation should be included in IPM
Marine benthos	Species-specific chronic responses in microcosms	Sediment exposure may be ecologically relevant
Fish	Residues and biological effects reported in experimental dosing	Aquatic exposure assessment should be use-specific
Field soil monitoring	EB1 detected in 97% of sampled Thai agricultural soils in one survey	Supports need for longitudinal monitoring

VIII. CONSUMER SAFETY, MRLS AND REGULATORY CONSIDERATIONS

Regulatory interpretation is essential because residue concentration alone does not determine dietary safety. Risk assessment considers the toxicological reference values, residue definition, food consumption pattern, commodity-



specific residue data and uncertainty. The WHO/FAO JMPR database currently lists an ADI of 0–0.0005 mg/kg body weight and an acute reference dose of 0.02 mg/kg body weight for emamectin based on the 2023 evaluation [39]. Field studies have generally reported dietary risk below critical thresholds under their specified Good Agricultural Practice conditions. For example, the 2023 cabbage study reported chronic and acute risk quotients below 100% under the tested scenarios [28], and the cowpea study reported acceptable dietary risk while showing that maturity and formulation affected residue decline [13]. These findings support rational use according to label directions but do not justify a blanket claim that emamectin benzoate is intrinsically risk-free.

IX. INTEGRATED DISCUSSION

The evidence assembled in this review supports a four-stage interpretation of emamectin benzoate use. First, the physicochemical characteristics of the macrocyclic lactone influence deposition, adsorption, plant penetration and environmental partitioning. Second, these properties contribute to effective exposure of target larvae and high biological activity through GluCl activation. Third, the same molecular and formulation characteristics influence how rapidly parent residues decline from crop surfaces and how transformation products are generated. Fourth, residues that leave the crop may enter soil, water or sediment and become relevant to non-target organisms depending on concentration and exposure duration.

An important synthesis concerns formulation. The cowpea comparison demonstrates that EC and ME formulations can have different dissipation kinetics [13], while delivery-system studies show that changes in formulation can alter foliar utilization and photostability [24,25]. Therefore, future residue studies should report formulation composition and application parameters in sufficient detail to permit comparison. Treating 'emamectin benzoate' as a single exposure scenario can conceal practically important differences.

Resistance is a synthesis. Emamectin benzoate's strong efficacy may promote repeated usage, however recent research shows resistance in a number of pests through metabolic and target-associated pathways [8–10,26]. Thus, resistance surveillance, mode-of-action rotation, and integration with IPM are necessary for sustainable efficacy. Since both residue management and resistance management are impacted by application rate, frequency, timing, and formulation, they should not be seen as separate topics.

Lastly, the literature shows an analytical shift from parent-compound measurement to multi-residue, metabolite-aware monitoring. High sensitivity is offered by contemporary LC-MS/MS and UPLC-MS/MS techniques, and transformation products are increasingly being included in investigations [28,31,34]. This is a good thing, but in order to compare data across crops, nations, and environmental compartments, standardized methods are still required.

IX. RESEARCH GAPS AND FUTURE PERSPECTIVES

- **Formulation-specific fate:** More studies should compare EC, SC, ME and newer delivery systems under identical field conditions, because formulation can alter dissipation and exposure.
- **Pulse crops and chickpea:** Residue and dissipation datasets for pulses, especially chickpea, remain less developed than datasets for several fruit and vegetable crops. Commodity-specific field trials are warranted.
- **Metabolite-aware residue analysis:** Future studies should simultaneously quantify parent emamectin B1a/B1b and toxicologically relevant photo-metabolites wherever the regulatory residue definition requires them.
- **Long-term soil monitoring:** Multi-season field monitoring is needed to distinguish single-application dissipation from accumulation under repeated agricultural use.

X. CONCLUSION

Emamectin benzoate's high potency, unique GluCl-mediated mode of action, and efficacy against significant insect pests make it a desirable pesticide. Its scientific assessment ought to go beyond bioefficacy, though. Regulatory evaluations reveal that photodegradation products and residue definitions can significantly impact risk interpretation,



whereas published data indicates that residue dissipation varies among crops, plant developmental stages, environmental compartments, and formulations. Environmental studies further show that various exposure patterns may be experienced by non-target species, soil, water, and sediment. At the same time, the necessity of appropriate and integrated use is highlighted by the emergence of resistance in important pests.

In order to maximize the agronomic value of emamectin benzoate while minimizing needless exposure to consumers and the environment, future research should prioritize formulation-specific field trials, pulse-crop residue studies, metabolite-aware analytical methods, long-term environmental monitoring, and integrated ecological risk assessment. Therefore, the most appropriate framework is not simply "effective versus unsafe," but rather an integrated assessment of efficacy, formulation behavior, residue kinetics, environmental fate, and resistance risk.

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