



Persistence of Tricyclazole and Tebuconazole Fungicides under Varying Moisture Conditions in Riverine Alluvium Soils of Kerala, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

This laboratory study examined the persistence and dissipation of tricyclazole and tebuconazole in riverine alluvium soil under two moisture regimes: field capacity and submergence. Each fungicide was introduced separately at 1, 2 and 4 mg kg⁻¹, and soil samples were collected at intervals from day 0 to day 75. Residues were extracted using a modified QuEChERS procedure and quantified by liquid chromatography–tandem mass spectrometry. Method validation showed recoveries of 90.04–94.76% for tricyclazole and 80.04–92.09% for tebuconazole, with relative standard deviations below 5%. The dissipation of both fungicides was generally described using first-order kinetics. Mean half-lives across the evaluated treatments were 12.85 days for tricyclazole and 9.86 days for tebuconazole. Mean half-lives under field-capacity and submerged conditions were 13.52 and 9.19 days, respectively, indicating lower persistence under submergence. For tricyclazole, treatment-specific half-lives ranged from 6.61 days under submerged conditions at 1 mg kg⁻¹ to 18.95 days under field capacity at 4 mg kg⁻¹. Tebuconazole also exhibited shorter half-lives under submerged conditions than under field capacity at corresponding concentrations. Persistence generally increased with the initial fungicide concentration, particularly for tricyclazole. These findings indicate that fungicide identity, moisture regime and initial concentration influence residue dissipation in the soil examined. The results provide laboratory-based evidence for assessing the behaviour of these fungicides under contrasting moisture conditions relevant to paddy soils.

Keywords: Tricyclazole; tebuconazole; fungicide persistence; riverine alluvium soil; soil moisture regime; field capacity, submerged conditions; pesticide residue dissipation; first-order kinetics; QuEChERS–LC-MS/MS.

1. Introduction

Agriculture faces the challenge of increasing food production while ensuring environmental sustainability and climate resilience. The growing demand for food has resulted in increased pesticide use worldwide, raising concerns regarding environmental contamination, soil persistence, effects on non-target organisms, and pesticide residues in food. Fungicides are particularly important in rice cultivation, where diseases such as blast, sheath blight and brown spot can substantially reduce yield, especially under Kerala's warm and humid conditions. Among the commonly used fungicides, tricyclazole and tebuconazole are important for managing rice diseases, necessitating an understanding of their environmental fate and persistence.

Tricyclazole is a systemic fungicide widely used against rice blast and acts by inhibiting melanin biosynthesis. It has relatively high water solubility (596 mg L⁻¹) and can persist in soil, while tebuconazole is a broad-spectrum systemic triazole fungicide used against rice blast and sheath blight, with a water solubility of 32 mg L⁻¹ and moderate persistence (Agriculture and Environment Research Unit, 2026). Concerns regarding pesticide residues, particularly tricyclazole in Basmati rice exports to the European Union, have further emphasised the importance of residue monitoring and appropriate fungicide management (Sen, 2017).

The fate of fungicides in soil is governed by adsorption–desorption, leaching, runoff, volatilisation and chemical and microbial degradation, with soil properties, moisture regime, climatic conditions, organic amendments and formulation influencing these processes (Fernandes *et al.*, 2006). Tricyclazole has shown variable persistence, with reported half-lives ranging from weeks to several months depending on environmental conditions, and generally stronger retention under dry conditions than under submerged conditions (Vogue *et al.*, 1994; Fernandes *et al.*, 2006; Kumar *et al.*, 2013). Similarly, tebuconazole exhibits variable persistence, with degradation influenced by soil characteristics, microbial activity and organic amendments; enhanced dissipation has been reported under amended and field conditions (Badawi *et al.*, 2016; Strickland *et al.*, 2004; Herrero-Hernández *et al.*, 2023).

Overall, the contrasting physicochemical properties and variable persistence of tricyclazole and tebuconazole highlight the need to investigate their adsorption, dissipation, mobility and uptake by rice under specific soil and moisture conditions. Such information is essential for understanding their chemodynamics and for developing environmentally safe and sustainable fungicide-management practices.

However, the studies reviewed above do not directly compare the persistence of tricyclazole and tebuconazole at the same concentration levels under field-capacity and submerged conditions in the riverine alluvium soil investigated here.

The objective of this study was therefore to determine and compare the dissipation and half-lives of tricyclazole and tebuconazole at 1, 2 and 4 mg kg⁻¹ under field-capacity and submerged conditions in riverine alluvium soil.

2. Materials and Methods

2.1 Chemical and Reagents

Certified reference materials of tricyclazole and tebuconazole were provided by Bayer CropScience, India. The commercial formulations used were marketed under the trade names Saikin (Tricyclazole 75% WP) and Folicur (250 EC). PSA (primary secondary amine) and a 0.2 µm PTFE membrane filter were procured from Agilent Technologies, Palo Alto, USA. Magnesium sulphate heptahydrate (MgSO₄·7H₂O), sodium chloride, sodium sulphate, sodium acetate, acetic acid, acetone, acetonitrile, n-hexane and toluene were procured from Merck India Pvt Ltd, India. The water used in sample preparation was purified using the ELGA water purification system

2.2 Experimental Details

The laboratory experiment was conducted using riverine alluvium soil collected from the experimental paddy field of IFSRS, Karamana (8.474102° N, 76.959137°E). The soil samples were analysed for physico-chemical properties such as texture, pH, CEC, EC and organic matter using standard procedures (Jackson, 1973). Studies on the persistence of tricyclazole and tebuconazole were conducted under field-capacity and waterlogged conditions at three spiking levels (1, 2 and 4 mg kg⁻¹) under laboratory conditions using their commercial formulations Saikin and Folicur, respectively. For the study, one kilogram of soil under each field-capacity and waterlogged condition was placed in a conical flask and spiked separately at 1, 2 and 4 mg kg⁻¹ levels of tricyclazole and tebuconazole, homogenised and kept aside for 2 h (day 0) from which 10 g soil was taken and analysed for residue estimation. Likewise, samples were drawn on days 1, 3, 5, 7, 10, 14, 21, 28, 35, 40, 50 and 75 for estimation of residues and to identify the metabolites formed. The persistence levels of both fungicides at different time intervals were recorded, and their respective half-lives were subsequently calculated.

2.3 Method Validation of Estimation of Residues

The analytical procedure for determining residues of the fungicides tricyclazole and tebuconazole in riverine alluvium soil was validated using a modified version of the standard method described by Anastassiades *et al.* (2003). Validation of the method involved evaluation of several analytical performance parameters, including recovery, linearity, accuracy, precision, repeatability, reproducibility, limit of detection (LOD) and limit of quantification (LOQ). Calibration curves were prepared using a series of standard solutions with different concentrations. According to European Commission guidelines (2019), concentrations producing signal-to-noise ratios of ≥ 3 and ≥ 10 were considered as the LOD and LOQ, respectively. In the present study, the LOD and LOQ values were established at 0.033 mg kg⁻¹ and 0.01 mg kg⁻¹, respectively. Method accuracy was assessed through percentage recovery, while precision was determined using the relative standard deviation (RSD %) of repeatability. Recovery experiments were performed by fortifying untreated riverine alluvium soil samples with analytical standards of tricyclazole and tebuconazole at concentrations of 0.01, 0.05, 0.1 and 0.5 mg kg⁻¹. Each fortification level was analysed in five replicates to evaluate the repeatability and reliability of the analytical procedure for pesticide residue estimation.

2.4 Extraction and Clean-up of Soil

Residues of tricyclazole and tebuconazole in soil samples were extracted following a modified QuEChERS procedure (Anastassiades *et al.*, 2003). For the extraction, 10 g of soil from each of the five replications was transferred into 50 mL centrifuge tubes, and 20 mL of acetonitrile was added. The mixture was vortexed for 2 min to ensure proper extraction of the analyte. Subsequently, 4 g sodium sulphate and 2 g sodium chloride were added sequentially, followed by vortex mixing for another 2 min. The samples were then centrifuged at 3300 rpm for 4 min at 20 °C.

The resulting extract was purified using dispersive solid-phase extraction (d-SPE). A 10 mL aliquot of the supernatant was transferred into a 15 mL centrifuge tube containing 0.25 g primary secondary amine (PSA) and 1.5 g magnesium sulphate. The mixture was vortexed for 30 s and centrifuged at 4400 rpm for 10 min. After purification, 4 mL of the cleaned extract was collected in a turbo tube and evaporated to dryness at 40 °C using a nitrogen evaporator. The resulting residue was reconstituted with methanol and the final volume was adjusted to 1 mL. The solution was then filtered through a 0.22 µm polyvinylidene fluoride (PVDF) syringe filter and transferred into LC vials for residue quantification using LC-MS/MS analysis.

2.5 Instrumentation

The extracted samples were analysed using LC-MS/MS for quantitative determination of pesticide residues. Chromatographic separation was performed using a Thermo Fisher Scientific Dionex Ultimate 3000 UHPLC system (Germering, Germany) equipped with an Accucore aQ column maintained at 30 °C. The mobile phase consisted of two solvent systems: solvent A containing 0.10% formic acid and 5 mM ammonium formate in water, and solvent B containing 0.10% formic acid and 5 mM ammonium formate in methanol. Gradient elution was employed, beginning with 10% solvent B held for 1.5 min, increased to 15% within 1.5 min, further raised to 90% by 5 min, then reduced to 50% at 6 min, followed by 30% at 7 min, and finally returned to the initial condition of 10% B at 10 min to allow column re-equilibration.

The flow rate was maintained at 0.3 mL min⁻¹ with a total run time of 10 min. The mass spectrometer operated with a heated electrospray ionisation (H-ESI) source in positive ionization mode. Instrument settings included sheath gas at 60 arbitrary units, auxiliary gas at 5 arbitrary units, and sweep gas at 1 arbitrary unit. The ion transfer tube temperature was maintained at 320 °C, spray voltage at 3800 V, and vaporiser temperature at 450 °C. Quantification of tricyclazole and tebuconazole was carried out using the TSQ Quantiva LC-MS/MS system (Thermo Scientific, San Jose, CA, USA). The optimised LC-MS/MS operating parameters for tricyclazole and tebuconazole are presented in Table 1.

Table 1. Liquid Chromatography (LC) parameters for tricyclazole and tebuconazole

Compound	Retention time (min)	Polarity	Precursor (m/z)	Product (m/z)	Collision energy (V)	Quantitative/Qualitative
Tricyclazole	5.23	Positive	190.1	136	29.00	Qualitative
			190.1	163	24.00	Quantitative
Tebuconazole	6.33	Positive	308.2	70.338	24.00	Qualitative
			308.2	125.106	35.00	Quantitative

2.6 Data Analysis

The degradation pattern and half-life of tricyclazole and tebuconazole residues were analysed following the statistical approach described by Hoskins (1961). The dissipation of tricyclazole and tebuconazole in soil was assumed to follow first-order kinetics and was represented by the equation $C_t = C_0 e^{-kt}$, where C_t denotes the concentration of fungicides at time t , C_0 represents the initial concentration immediately after application, and k is the degradation rate constant. The half-life ($t_{1/2}$), defined as the time required for the residue concentration to decline to half of its initial value, was calculated using the expression

$$t_{1/2} = \ln(2)/k.$$

The effects of fungicide type, moisture regime and fungicide concentration on the half-life values were analysed using a three-factor factorial analysis. Statistical analysis was carried out using GRAPES developed by Kerala Agricultural University.

3. Results and Discussion

3.1 Physico- chemical properties of the soil

The physicochemical properties of the soil sample are given in Table 2. The soil had a sandy loam texture with 57.84% sand, 23.20% silt and 14.40% clay, respectively. The bulk density was 1.44 Mg m⁻³ and the water-holding capacity was 14.64%. The soil pH and EC were 5.61 and 0.2 d S m⁻¹, respectively. The organic carbon content was 1.07%. The available primary nutrients were nitrogen (248.53 kg ha⁻¹); phosphorus (25.68 kg ha⁻¹); potassium (130 kg ha⁻¹), respectively. The secondary nutrients calcium, magnesium and sulphur were 230, 132, and 98 mg kg⁻¹, respectively. Thus, the riverine alluvium soil had medium levels of available nitrogen and potassium and a high level of available phosphorus. Exchangeable calcium was deficient, whereas magnesium and sulphur were sufficient in the soil. The concentrations of major micronutrients viz. Fe, Cu, Mn and Zn were 43.19, 0.88, 38.2 and 1.41 mg kg⁻¹ respectively.

3.2 Recovery Experiments

The recovery of tricyclazole and tebuconazole from soil was evaluated at four spiking levels (0.01–0.50 mg kg⁻¹) using QuEChERS and traditional extraction methods. QuEChERS consistently showed higher recoveries, ranging from 90.04–94.76% for tricyclazole and 80.04–92.09% for tebuconazole, compared with 65.48–67.79% and 60.31–68.77%, respectively, for the traditional method, with RSD values below 5% for both fungicides. The recovery and precision values satisfied the SANTE/12682/2019 acceptance criteria of 70–120% recovery and <20% RSD, supporting the suitability of the QuEChERS method for residue estimation. The retention times of tricyclazole and tebuconazole were 5.23 and 6.33 min, respectively. The detailed recovery results are presented in Tables 3 and 4.

Table 2. Physico chemical properties of riverine alluvium soil of IFSRS, Karamana

Sl. No	Parameters	Results
I.	Mechanical composition	
1.	Texture	Sandy loam
2.	Sand (%)	57.84
3.	Silt (%)	23.20
4.	Clay (%)	14.40
II.	Physical properties	
5.	Bulk density (Mg m ⁻³)	1.30
6.	Particle density (Mg m ⁻³)	2.40
7.	Porosity (%)	45.80
8.	Field moisture (%)	12.75
9.	Water Holding Capacity (WHC) (%)	14.64
10.	Hydraulic conductivity (mL min ⁻¹)	
III.	Chemical properties	
11.	pH	5.61
12.	Electrical conductivity (EC, dS m ⁻¹)	0.2
13.	Cation Exchange Capacity (CEC) (cmol (+) kg ⁻¹)	5.18
14.	Anion Exchange Capacity (AEC) (cmol (-) kg ⁻¹)	1.26
15.	Organic Carbon (OC) (%)	1.07
16.	Available Nitrogen (kg ha ⁻¹)	248.53
17.	Available Phosphorus (kg ha ⁻¹)	25.68
18.	Available Potassium (kg ha ⁻¹)	130
19.	Available Calcium (mg kg ⁻¹)	230
20.	Available Magnesium (mg kg ⁻¹)	132
21.	Available Sulphur (mg kg ⁻¹)	98
22.	Available Fe (mg kg ⁻¹) (0.1 N HCl)	43.19
23.	Available Cu (mg kg ⁻¹) (0.1 N HCl)	0.88
24.	Available Mn (mg kg ⁻¹) (0.1 N HCl)	38.20
25.	Available Zn (mg kg ⁻¹)	1.44

Table 3. Recovery of tricyclazole at different levels of spiking in soil

Level (mg kg ⁻¹)	QuEChERS method			Traditional method		
	Recovery Percentage	Standard deviation	Relative Standard deviation (RSD) %	Recovery Percentage	Standard deviation	Relative Standard deviation (RSD) %
0.01	90.04	0.47	0.53	65.48	2.06	3.05
0.05	92.83	2.26	2.43	65.76	1.75	2.52
0.10	93.79	1.99	2.13	66.34	3.27	4.55
0.50	94.76	4.39	4.63	67.79	1.84	2.55

Table 4. Recovery of tebuconazole at different levels of spiking in soil

Level (mg kg ⁻¹)	QuEChERS method			Traditional method		
	Recovery Percentage	Standard deviation	Relative Standard deviation (RSD) %	Recovery Percentage	Standard deviation	Relative Standard deviation (RSD) %
0.01	80.04	0.47	0.59	61.64	2.69	4.37
0.05	86.16	3.37	3.91	60.31	3.64	6.04
0.10	91.46	1.53	1.67	63.22	4.17	6.60
0.50	92.09	1.46	1.58	68.77	1.74	2.53

3.3 Dissipation of Fungicides

The dissipation of tricyclazole in riverine alluvium soil was evaluated under field-capacity and submerged moisture regimes at initial concentrations of 1, 2 and 4 mg kg⁻¹ (C1, C2 and C3, respectively) over 75 days (Tables 5 and 6). Under field-capacity conditions, residues declined progressively, with half-lives of 12.26, 16.95 and 18.96 days for C1, C2 and C3, respectively. Residues at C1 and C2 declined below the LOQ by 50 and 75 days, respectively, whereas C3 remained detectable at 0.067 mg kg⁻¹ at 75 days. Under submerged conditions, dissipation was considerably faster, with half-lives of 6.62, 10.73 and 11.68 days for C1, C2 and C3, respectively; residues declined below the LOQ by days 28, 40 and 75, respectively, with final dissipation of 92.50, 92.31 and 98.00%.

The dissipation kinetics followed first-order decay under both moisture regimes, with regression coefficients (R^2) of 0.9271–0.9869 under field capacity and 0.8602–0.9790 under submerged conditions. Dissipation rate constants were consistently higher under submerged conditions (0.062–0.105 day⁻¹) than under field capacity (0.037–0.056 day⁻¹), indicating enhanced dissipation under flooded conditions. Overall, tricyclazole persistence increased with increasing initial concentration, while submergence substantially accelerated its dissipation compared with field-capacity conditions (Fig.1).

The dissipation of tebuconazole in riverine alluvium soil was evaluated under field-capacity and submerged moisture regimes at initial concentrations of 1, 2 and 4 mg kg⁻¹ (C1, C2 and C3, respectively) over 75 days (Tables 7 and 8). Under field-capacity conditions, residues declined progressively and reached below the LOQ by 75 days at all concentrations, with half-lives of 9.38, 11.58 and 12.06 days for C1, C2 and C3, respectively. Under submerged conditions, dissipation was faster, with residues at C1 falling below the LOQ by 50 days and those at C2 and C3 by 75 days; corresponding half-lives were 8.20, 8.81 and 9.19 days, respectively.

Tebuconazole dissipation generally followed first-order kinetics, with a better fit under submerged conditions ($R^2 = 0.9200$ – 0.9409) than under field capacity ($R^2 = 0.7736$ – 0.8602). The dissipation rate constants under submerged conditions (0.075–0.085 day⁻¹) were higher than those under field capacity (0.057–0.060 day⁻¹ for the first-order treatments), confirming enhanced dissipation under flooded conditions (Fig 2). Across both moisture regimes, half-life increased with increasing initial concentration, particularly under field-capacity conditions, indicating concentration-dependent persistence. Overall, submergence accelerated tebuconazole dissipation, resulting in shorter half-lives and higher dissipation rate constants than under field-capacity conditions.

The degradation of pesticides in soil is closely related to factors such as soil type, pH, organic matter content, cation exchange capacity and microorganisms (Morris *et al.*, 2018; Guimarães *et al.*, 2018; Saez *et al.*, 2018). The half-life of the fungicides was significantly influenced by fungicide type, moisture regime and their interactions. Tricyclazole exhibited a higher overall mean half-life (12.85 days) than tebuconazole (9.86 days), indicating greater persistence in riverine alluvium soil. Field-capacity conditions resulted in a higher mean half-life (13.52 days) than submerged conditions (9.19 days), indicating faster dissipation under submergence. The mean half-lives at 1, 2 and 4 mg kg⁻¹ were 12.97, 11.99 and 12.67 days, respectively.

The interaction between fungicide and moisture regime showed that tricyclazole had a substantially higher half-life under field capacity (16.04 days) than under submergence (9.66 days), while the corresponding values for tebuconazole were 10.99 and 8.74 days, respectively. Increasing concentration generally increased persistence, particularly for tricyclazole, with half-lives increasing from 9.43 to 15.30 days across 1–4 mg kg⁻¹, compared with 8.78–10.63 days for tebuconazole. Similarly, the mean half-life increased from 10.80 to 15.51 days with increasing concentration under field capacity and from 7.41 to 10.43 days under submerged conditions (Table 9). The greater persistence at higher concentrations may be associated with concentration-dependent inhibition of microbial degradation, as reported by George *et al.* (2007).

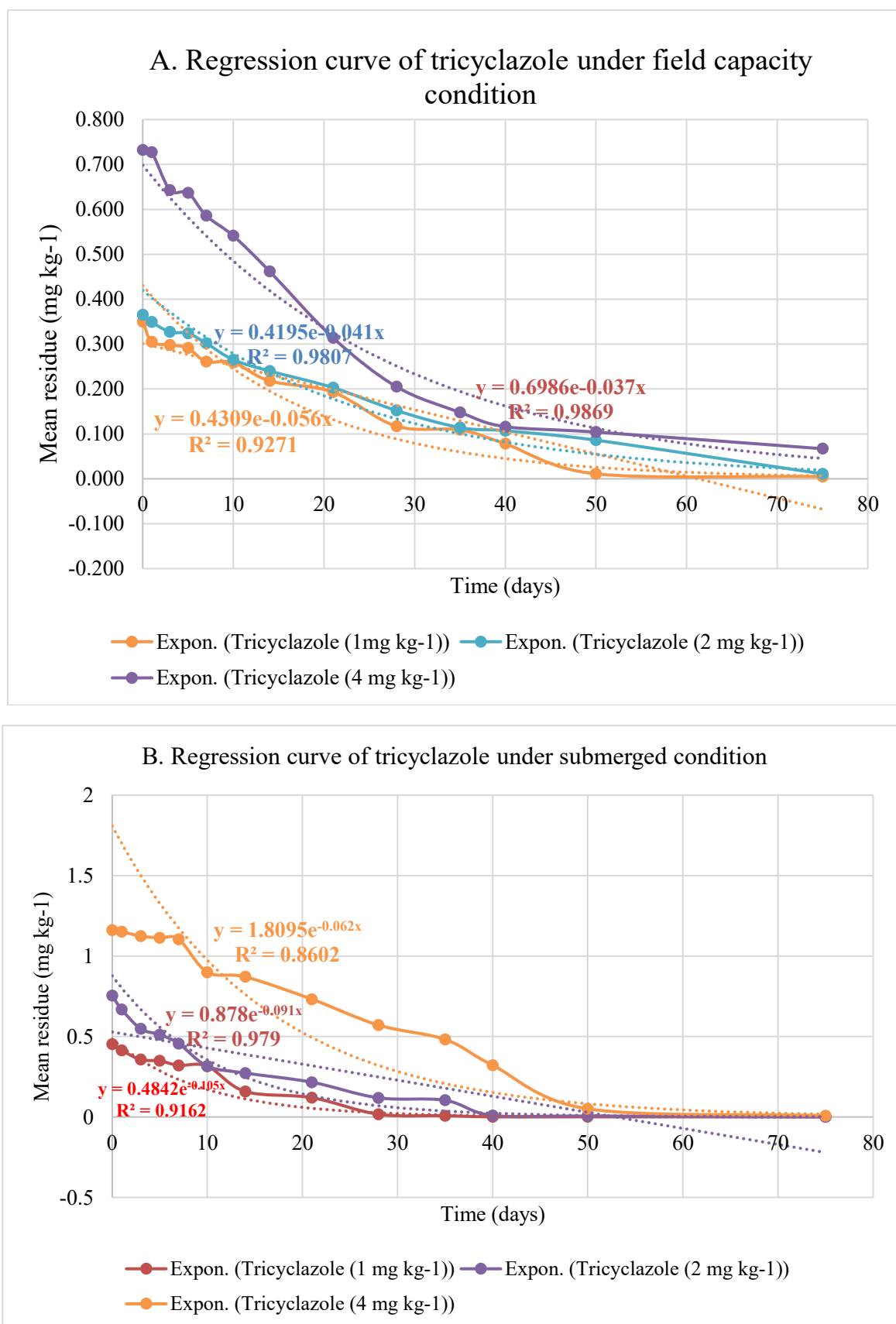


Fig 1. Dissipation kinetics of tricyclazole A) Field capacity B) Submerged moisture conditions

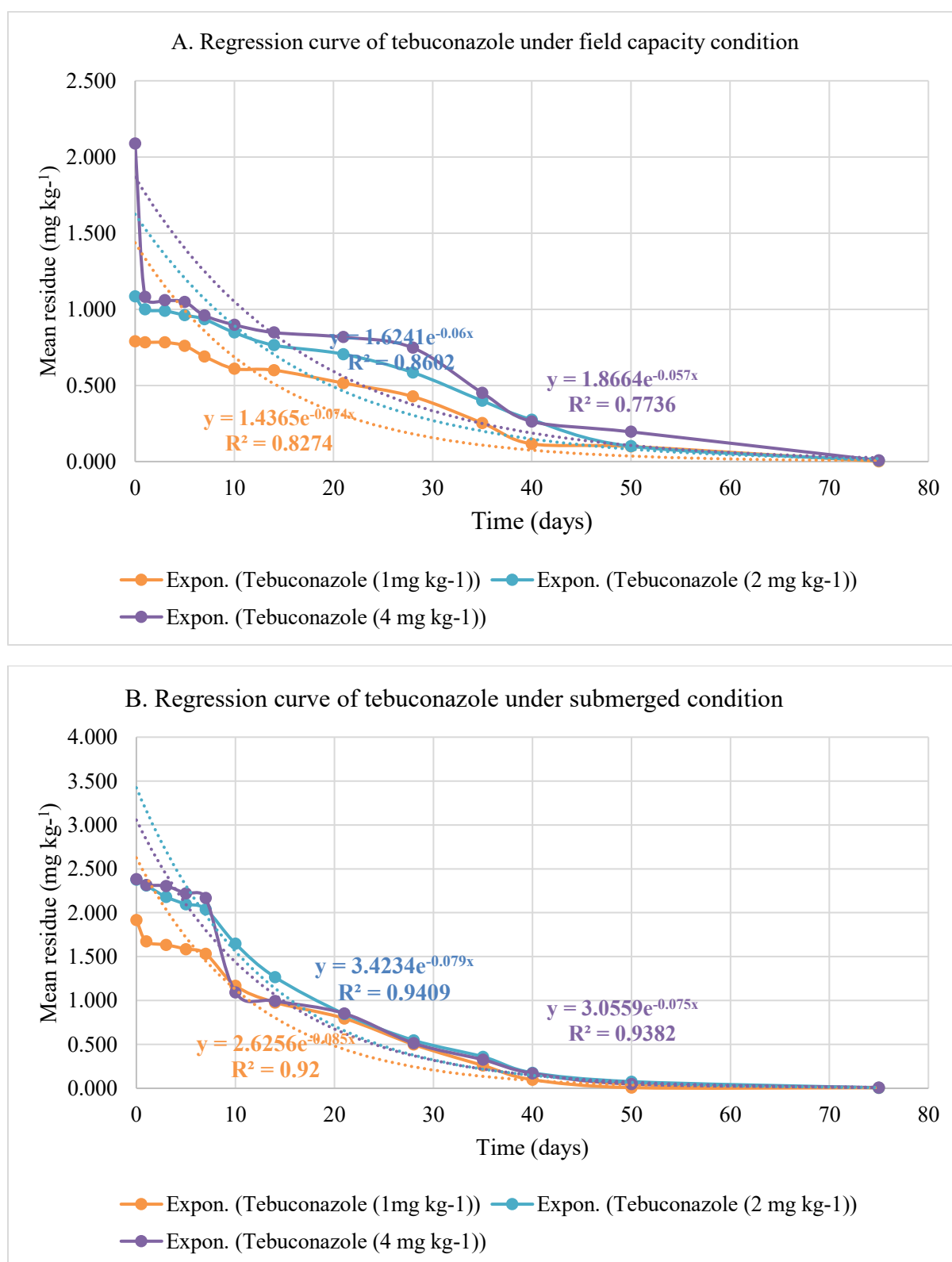


Fig 2. Dissipation kinetics of tebuconazole A) Field capacity B) Submerged moisture conditions

The three-way interaction further showed that the longest half-life (18.95 days) occurred for tricyclazole at 4 mg kg^{-1} under field-capacity conditions, whereas the shortest (6.61 days) was observed at 1 mg kg^{-1} under submerged conditions. Overall, the persistence pattern was tricyclazole > tebuconazole and field capacity > submerged conditions, with the effect of moisture being

more pronounced for tricyclazole (Table 10). These findings indicate that fungicide type, application concentration and soil moisture regime collectively regulate fungicide persistence in riverine alluvium soil.

Table 5. Dissipation of tricyclazole (F1) in riverine alluvium soil at field capacity (M1)

Treatment	Residues (mg kg ⁻¹) of tricyclazole (F1) in in riverine alluvium soil - field capacity moisture condition (M1)					
	C1 (1 mg kg ⁻¹ in soil)		C2 (2 mg kg ⁻¹ in soil)		C3 (4 mg kg ⁻¹ in soil)	
Days after treatment	Mean Residues ± SD	Dissipation (%)	Mean Residues ± SD	Dissipation (%)	Mean Residues ± SD	Dissipation (%)
0 th	0.350± 0.03		0.365± 0.02		0.732± 0.03	
1 st	0.305± 0.03	12.86	0.349± 0.03	4.38	0.727± 0.03	0.68
3 rd	0.298± 0.02	14.86	0.327± 0.01	10.41	0.643± 0.02	12.16
5 th	0.291± 0.02	16.86	0.324± 0.02	11.23	0.637± 0.01	12.98
7 th	0.261± 0.03	25.43	0.302± 0.02	17.26	0.586± 0.01	19.95
10 th	0.259± 0.01	26.00	0.265± 0.01	27.40	0.541± 0.02	26.09
14 th	0.218± 0.02	37.71	0.240± 0.01	34.25	0.462± 0.03	36.89
21 st	0.193± 0.03	44.86	0.203± 0.02	44.38	0.314± 0.03	57.10
28 th	0.117± 0.02	66.57	0.152± 0.02	58.36	0.205± 0.03	72.00
35 th	0.109± 0.01	68.86	0.114± 0.02	68.77	0.148± 0.02	79.78
40 th	0.078± 0.01	77.71	0.107± 0.03	70.68	0.116± 0.02	84.15
50 th	LOQ	-	0.086± 0.01	76.44	0.104± 0.01	85.79
75 th	LOQ	-	LOQ	-	0.067± 0.02	90.85
T ½ (Half-life)	12.26		16.95		18.96	

(LOQ-Limit of quantification (0.01 mg kg⁻¹), SD- standard deviation, C- concentration of tricyclazole, M- moisture condition, t_{1/2}- half-life)

Table 6. Dissipation of tricyclazole (F1) in riverine alluvium soil at submerged moisture condition (M2)

Treatment	Residues (mg kg ⁻¹) of tricyclazole (F1) in in riverine alluvium soil - submerged moisture condition (M2)					
	C1 (1 mg kg ⁻¹ in soil)		C2 (2 mg kg ⁻¹ in soil)		C3 (4 mg kg ⁻¹ in soil)	
Days after treatment	Mean Residues ± SD	Dissipation (%)	Mean Residues ± SD	Dissipation (%)	Mean Residues ± SD	Dissipation (%)
0 th	0.453± 0.02		0.754±0.02		1.161± 0.03	
1 st	0.414± 0.03	8.61	0.668±0.02	11.41	1.152± 0.03	0.78
3 rd	0.357± 0.03	21.19	0.548±0.02	27.32	1.124± 0.02	3.19
5 th	0.349± 0.01	22.96	0.512±0.01	32.10	1.113± 0.01	4.13
7 th	0.321± 0.02	29.14	0.456±0.01	39.52	1.105± 0.01	4.82
10 th	0.316±0.03	30.24	0.316±0.02	58.09	0.900± 0.02	22.48
14 th	0.158±0.01	65.12	0.273±0.01	63.79	0.871± 0.03	24.98
21 st	0.120±0.01	73.51	0.216± 0.03	71.35	0.732± 0.03	36.95
28 th	LOQ	-	0.119± 0.03	84.22	0.571± 0.03	50.82
35 th	LOQ	-	0.104± 0.01	86.21	0.482± 0.02	58.48
40 th	LOQ	-	LOQ	-	0.322± 0.02	72.27
50 th	LOQ	-	LOQ	-	0.051± 0.01	95.61
75 th	LOQ	-	LOQ	-	LOQ	-
T ½ (Half-life)	6.62		10.73		11.68	

(LOQ-Limit of quantification (0.01 mg kg⁻¹), SD- standard deviation, C- concentration of tricyclazole, M- moisture condition, t_{1/2}- half-life)

Table 7. Dissipation of tebuconazole (F2) in riverine alluvium soil at field capacity (M1)

Treatment	Residues (mg kg ⁻¹) of tebuconazole (F2) in in riverine alluvium soil - field capacity (M1)					
	C1 (1 mg kg ⁻¹ in soil)		C2 (2 mg kg ⁻¹ in soil)		C3 (4 mg kg ⁻¹ in soil)	
Days after treatment	Mean Residues ± SD	Dissipation (%)	Mean Residues ± SD	Dissipation (%)	Mean Residues ± SD	Dissipation (%)
0 th	0.790± 0.02		1.085± 0.04		2.087± 0.03	
1 st	0.783± 0.01	0.89	0.999± 0.03	7.93	1.081± 0.03	48.22
3 rd	0.782± 0.04	1.01	0.989± 0.02	8.85	1.059± 0.02	49.26
5 th	0.760± 0.03	3.80	0.961± 0.02	11.43	1.048± 0.01	49.79
7 th	0.690± 0.03	12.66	0.934± 0.01	13.92	0.959± 0.01	54.07
10 th	0.610± 0.01	22.78	0.847± 0.01	21.94	0.898± 0.01	56.98
14 th	0.600± 0.02	24.05	0.764± 0.02	29.59	0.847± 0.02	59.42
21 st	0.515± 0.02	34.81	0.705± 0.02	35.02	0.817± 0.02	60.86
28 th	0.427± 0.01	45.95	0.585± 0.01	46.11	0.747± 0.03	64.21
35 th	0.253± 0.01	67.97	0.399± 0.02	63.25	0.451± 0.02	78.39
40 th	0.116± 0.03	85.32	0.275± 0.03	74.70	0.263± 0.03	87.40
50 th	0.099± 0.02	87.47	0.101± 0.03	90.74	0.195± 0.01	90.66
75 th	LOQ	-	LOQ	-	LOQ	-
T ½ (Half-life)	9.38		11.58		12.06	

(LOQ-Limit of quantification (0.01 mg kg⁻¹), SD- standard deviation, C- concentration of tricyclazole, M- moisture condition, t_{1/2}- half-life)

Table 8. Dissipation of tebuconazole (F2) in riverine alluvium soil at submerged (M2)

Treatment	Residues (mg kg ⁻¹) of tebuconazole (F2) in riverine alluvium soil - submerged moisture condition (M2)					
	C1 (1 mg kg ⁻¹ in soil)		C2 (2 mg kg ⁻¹ in soil)		C3 (4 mg kg ⁻¹ in soil)	
Days after treatment	Mean Residues ± SD	Dissipation (%)	Mean Residues ± SD	Dissipation (%)	Mean Residues ± SD	Dissipation (%)
0 th	1.917± 0.02		2.377± 0.01		2.383± 0.01	
1 st	1.675± 0.03	12.62	2.311± 0.01	2.78	2.317± 0.02	2.77
3 rd	1.635± 0.01	14.71	2.181± 0.02	8.25	2.304± 0.02	3.32
5 th	1.586± 0.02	17.27	2.098± 0.02	11.74	2.220± 0.03	6.84
7 th	1.532± 0.01	20.08	2.040± 0.03	14.18	2.170± 0.02	8.94
10 th	1.170± 0.02	38.98	1.648± 0.02	30.67	1.094± 0.0	54.09
14 th	0.979± 0.02	48.95	1.267± 0.01	46.70	0.995± 0.03	58.25
21 st	0.796± 0.03	58.48	0.847± 0.02	64.37	0.853± 0.02	64.20
28 th	0.499± 0.03	73.97	0.547± 0.03	76.98	0.514± 0.01	78.43
35 th	0.260± 0.02	86.44	0.360± 0.01	84.87	0.326± 0.01	86.32
40 th	0.098± 0.01	94.89	0.177± 0.03	92.56	0.170± 0.02	92.87
50 th	LOQ	-	0.076± 0.02	96.79	0.048± 0.03	97.99
75 th	LOQ	-	LOQ	-	LOQ	-
T ½ (Half-life)	8.20		8.81		9.19	

(LOQ-Limit of quantification (0.01 mg kg⁻¹), SD- standard deviation, C- concentration of tricyclazole, M- moisture condition, t_{1/2}- half-life)**Table 9. Comparison of half- life values of tricyclazole and tebuconazole as influenced by the interaction effect of two factors**

Interactions	Mean half-lives (days)	Significant groups
Interaction of Fungicides (F) X Moisture conditions (M)		
F ₁ M ₁	16.042	a
F ₁ M ₂	9.662	c
F ₂ M ₁	10.991	b
F ₂ M ₂	8.735	d
CD (0.05)	0.02	
SE (m)	0.007	
Interaction of Fungicides (F) X Concentrations (C)		
F ₁ C ₁	9.434	d
F ₁ C ₂	13.821	b
F ₁ C ₃	15.301	a
F ₂ C ₁	8.780	f
F ₂ C ₂	10.176	d
F ₂ C ₃	10.633	c
CD (0.05)	0.024	
SE (m)	0.008	
Interaction of Moisture conditions (M) X Concentrations (C)		
M ₁ C ₁	10.802	c
M ₁ C ₂	14.239	b
M ₁ C ₃	15.508	a
M ₂ C ₁	7.411	f
M ₂ C ₂	9.759	e
M ₂ C ₃	10.426	d
CD (0.05)	0.024	
SE (m)	0.008	

Table 10. Comparison of half- life values as influenced by the interaction effect of type of fungicides, concentration levels and soil moisture conditions

Half-life values (days)				
Treatments/ Concentration-C	Tricyclazole (F1)		Tebuconazole (F2)	
	Field capacity (M1)	Submerged (M2)	Field capacity (M1)	Submerged (M2)
C1 (1 mg kg ⁻¹ in soil)	12.26	6.61	9.35	8.21
C2 (2 mg kg ⁻¹ in soil)	16.92	10.72	11.56	8.80
C3 (4 mg kg ⁻¹ in soil)	18.95	11.65	12.07	9.20
CD (0.05) interaction (F×M×C) = 0.034				
SE(m) interaction (F×M×C) = 0.012				

(CD – critical difference; SE(m) - standard error of the mean, F- Fungicides; C- concentration; M- moisture condition)

The present findings are consistent with previous reports demonstrating greater pesticide persistence under dry conditions than under field-capacity or submerged conditions (Gupta *et al.*, 2008; Miles *et al.*, 1984; Das & Mukherjee, 2012). The faster

dissipation observed under submerged conditions may be attributed to enhanced microbial activity and the development of anaerobic conditions that favour degradation, as reported for pendimethalin, cyfluthrin and other pesticides (Kulshrestha & Singh, 1992; Smith *et al.*, 1995; George *et al.*, 2007). Thus, soil moisture and associated redox conditions are important determinants of pesticide dissipation, with flooded conditions generally being associated with faster dissipation.

4. Conclusion

The dissipation of tricyclazole and tebuconazole in riverine alluvium soil was influenced by fungicide type, initial concentration and soil moisture regime. The modified QuEChERS–LC-MS/MS method provided satisfactory recovery and precision for residue determination. Tricyclazole was more persistent than tebuconazole, with mean half-lives of 12.85 and 9.86 days, respectively, while both fungicides dissipated faster under submerged conditions than at field capacity. Increasing initial concentration generally increased persistence, with the longest half-life (18.95 days) recorded for tricyclazole at 4 mg kg⁻¹ under field capacity and the shortest (6.61 days) at 1 mg kg⁻¹ under submerged conditions. Overall, the persistence pattern was tricyclazole > tebuconazole and field capacity > submerged conditions, indicating the importance of fungicide concentration and water regime when assessing pesticide fate in paddy soils. Further field-scale studies incorporating seasonal variation, repeated applications, residue transport and transformation products are warranted to strengthen environmental risk assessment.

5. Limitations

The findings were obtained from laboratory incubation of one riverine alluvium soil under two moisture regimes and three initial fungicide concentrations. Therefore, extrapolation to other soil types and field-management conditions requires caution. The results characterise residue dissipation during a 75-day observation period and do not establish how the observed half-lives vary across seasons or under repeated field applications. Field investigations involving additional soils and moisture-management settings would help assess the wider applicability of the reported persistence patterns.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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