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Pesticide residues in organic vs. conventional rice systems: Management recommendations for Vietnam's Mekong Delta

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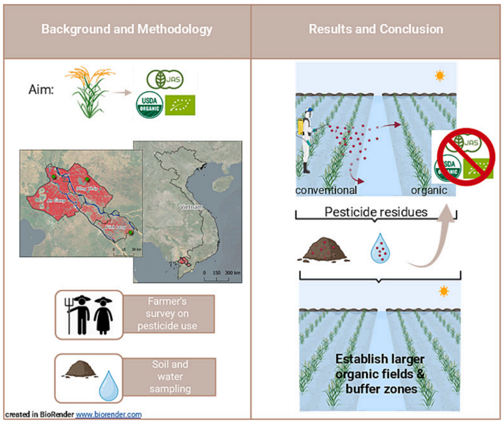
HIGHLIGHTS

- Comprehensive study of farmer pesticide use in rice farming in the Mekong Delta, Vietnams larges rice production area.
- Soil and water analysis of pesticide residues in organic and conventional fields across three provinces.
- Shared water sources are a major cause of pesticide cross-contamination.
- Farmer cooperatives, larger organic areas and wider buffers to conventional fields can mitigate pesticide pollution.
- Provides insights and recommendations to guide Mekong Delta farmers and stakeholders towards sustainable rice farming.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Intensified paddy rice production in Vietnam, particularly in the Mekong Delta, has led to a significant increase in chemical pesticide use over recent decades, resulting in widespread contamination of agricultural soils and water sources. Vietnam's Mekong Delta, a key region for national rice production and rice exports, holds predominantly smallholder farming with fields typically spanning just 1–2 ha per farmer. This fragmented structure challenges coordinated management and organic certification efforts, while limited data on pesticide use and residues levels challenges system-level evaluations for sustainable transitions.

OBJECTIVE: This study investigated pesticide application patterns in conventional rice farming across three provinces, An Giang, Đồng Tháp, and Vĩnh Long in the Mekong Delta to assess implications for sustainable organic rice production systems.

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METHODS: Farmer interviews documented pesticide use, while soil and water samples from conventionally and organically managed fields were collected to evaluate contamination levels and potential cross-contamination pathways.

RESULTS AND CONCLUSIONS: Results showed a wide range of pesticides applied in conventional rice farming, with soil residues reflecting the reported usage. Thus, the detection of compounds not reported by farmers indicated cross-contamination from neighboring land uses. Notably, pesticide residue levels in some organic fields were comparable to those in conventional ones, suggesting contamination via shared water sources or close distance to treated areas. These findings highlight major challenges for organic rice transitions in smallholder dominated landscapes, emphasizing the need for farmer cooperatives, enhanced cooperation, larger buffer zones and stricter spatial separation between conventional and organic fields to reduce pesticide intrusion.

SIGNIFICANCE: This study provides critical insights and practical recommendations to support farmers and stakeholders throughout the Mekong Delta region to identify effective measures for advancing the transition towards more sustainable rice farming practices.

1. Introduction

The Mekong Delta, often referred to as the “Rice Bowl” of Vietnam, plays a crucial role in the nation's food security and economic stability. The region contributes 56% of Vietnam's total rice production (GSO, 2023) and accounts for 90% of the countries rice export volume, which makes Vietnam one of the largest exporters of rice products worldwide (Kontgis et al., 2019; Nguyen et al., 2022). To sustain the national food security and its leading position, Vietnam has intensified paddy rice production over recent decades, adopting high-yield varieties and increasing fertilizer and pesticide use (Nguyen et al., 2022). However, the reliance on pesticides, driven by the “Green Revolution”, initially aiming at boosting agricultural productivity in the Global South, led to widespread pesticide overuse, environmental contamination, and health risks (Tostado et al., 2022). In general, land reforms and rising rural incomes increased pesticide accessibility and use in many developing countries, while inadequate training often led to overuse (Giang et al., 2022; Migheli, 2017). In 2023, about 3.7 million tons (FAO, 2023) of pesticides have been used worldwide and especially in developing countries, the application of pesticides has increased to maintain or increase the levels of crop production. With nearly 162,000 tons of pesticides used for agricultural purposes in 2023, the pesticide use has also doubled in the past ten years in Vietnam (FAO, 2023). The intensified application of pesticides is causing widespread contamination in water resources including drinking water via drainage through the soil profile, surface runoff, and spray drift (Braun et al., 2019; Chau et al., 2015; Van Toan et al., 2013). The reliance on pesticides in rice cultivation has shown to be problematic and unsustainable since pesticide-induced outbreaks of pests and the development of pesticide resistances were reported (Gao et al., 2025; Nguyen et al., 2022). At the same time, climate related stress on the plants and biodiversity loss have contributed to the increase of pesticide application (Tostado et al., 2022). Intensive pesticide use has made agriculture one of the most hazardous occupations globally, with unintentional exposure causing severe health risks (O'Connor et al., 2025). Since the global ban on organochlorine pesticides, newer pesticide classes such as carbamates, pyrethroids, and phenyl pyrazoles have been introduced, valued for their high target toxicity, rapid decomposition, and lower bioaccumulation potential. However, these benefits have led to a misconception among farmers that these pesticides are harmless to humans and the environment, resulting in misuse and increased risks of dietary pesticide exposure (Giang et al., 2022).

The WHO estimates 2–5 million pesticide poisonings annually, with around 40,000 fatalities (Nankongnab et al., 2020; Tostado et al., 2022). As pesticides are mobile either in their dissolved phase or transported while being bound to particles, their transport in the environment is difficult to control and they often contaminate the environment or can end up in drinking water and food products (Chau et al., 2015; Tostado et al., 2022). According to the 2020 European report by the European Food Safety Authority (EFSA), 34.5% of the 802 analyzed rice samples contained detectable pesticide residues, with 6.7% exceeding the maximum residue level. Residue exceedances have been detected in rice samples from Asian countries such as India, Pakistan, and Vietnam, as well as rice tested within European countries, highlighting the ongoing challenges in controlling pesticide residues in rice products (EFSA, 2020).

Van Toan et al. (2013) identified pesticide residues in surface waters in Đồng Tháp Province and Can Tho City in Vietnam, including herbicides (Butachlor, Pretilachlor, Propanil) and insecticides (Buprofezin, Cypermethrin, Endosulfan, Fenobucarb, Fipronil, Profenofos), with the highest concentrations found for fungicides like Propiconazole and Isoprothiolane. Similarly, Braun et al. (2019) reported pesticide residues in soils from Bến Tre and Sóc Trăng Provinces in Vietnam, including high concentrations of Isoprothiolane (67.1 μg kg^{-1}) and Propiconazole (41.7 μg kg^{-1}) among others. Duong et al. (2022) detected 17 pesticide residues in soil and rice samples from organic rice farming, emphasizing the need for ongoing monitoring of pesticides in the Mekong Delta. Despite the importance of rice production in the Mekong Delta, data on actual pesticide use, application rates, and resulting residues remain limited and often fragmented in both scope and coverage. There are notable gaps concerning the spatial and temporal monitoring of pesticide residues in this region, making risk assessment and the development of sustainable management strategies challenging (Dirikumo, 2023; Landos, 2024).

Given the need to better understand pesticide use and contamination in the Mekong Delta, this research focuses on evaluating pesticide use and pesticide residues in the provinces of Vĩnh Long, An Giang, and Đồng Tháp. These provinces are situated along the Mekong River - a crucial water source for rice farming and a critical pathway for pesticide transport across the Mekong Delta into the ocean. The study was based on farmer interviews to assess pesticide use patterns across the provinces and analyzed soil and water samples screened for ~750 pesticides. This comprehensive approach aims to provide a representative understanding of pesticide contamination in the Mekong Delta, which is a key for establishing organic farming practices in the highly intensified rice production area of the Mekong Delta and to guide decision makers in pesticide reduction measures.

2. Methods

2.1. Study sites

The Mekong Delta river is the 12th-longest river worldwide (Mekong River Commission, 2024). The river originates on the Qinghai-Tibet Plateau and flows through six countries - China, Myanmar, Laos, Thailand, Cambodia, and Vietnam—before emptying into the South China Sea (Li et al., 2017; Mekong River Commission, 2024). With an annual water discharge of 470 km^3 and an average annual sediment discharge of 160 million tons per year, its floodwaters deposit fertile sediments from the upper basin on the fields and wetlands of Vietnam

(Le et al., 2007). The Vietnamese Mekong Delta, the country's largest agricultural region, covers approximately 39,000 km^2, with about 2.6 million hectares dedicated to agricultural production (GSO, 2023; Le et al., 2007; Nguyen et al., 2022). Tropical monsoonal climate (mean annual temperature of 27 °C and annual rainfall of 1800 mm) results in a dry season from December to April and a rainy season from May to November. The nine distributaries of the Mekong River usually flood the Delta from end of September until late October or early November (Braun et al., 2019; Kontgis et al., 2019). The Sông Hậu River branches off the Mekong near Phnom Penh in Cambodia and is the primary distributary entering the Vietnamese Mekong Delta to the west, while the main branch of the Mekong flows into the delta further east. For this study, the study sites were located in the provinces of Vĩnh Long, An Giang, and Đồng Tháp. These provinces, account for one-third of the Mekong Delta's rice cultivation (GSO, 2023) and are located along the two main river branches Sông Hậu and Mekong, which branches off along Vĩnh Long province into the Sông Cổ Chiên River. The study sites in An Giang and Đồng Tháp are dominantly affected by flooding, whereas farmers in Vĩnh Long mainly irrigate their fields through pumping water from irrigation channels.

2.2. *Farmer survey*

A field survey was conducted across the three selected provinces between April 2023 and May 2024 (Fig. 1). In order to assess potential pesticide pollution and residue exposure in the region, the survey aimed to identify the types of pesticides applied in rice cultivation. A semi-structured questionnaire (Table S1) was designed to gather information from farmers regarding their pesticide use practices, including the types of products applied, application frequency, and farmers' knowledge and perceptions related to pesticide use. In addition, the interviewees took photos of product labels during the interviews or of discharged pesticide containers and packages. The active ingredients of all reported pesticides were identified by examining the labels on collected packages documented by the photos. This approach enabled cross-verification of farmer-reported data and ensured a more accurate identification of the pesticide products in use. The resulting dataset provides a comprehensive overview of pesticide use in rice cultivation over a one-year period, providing insights into the commonly applied substances and their general occurrence across the study region. These data form the basis for estimating potential pesticide exposure scenarios relevant to environmental and human health risk assessments.

2.3. *Soil and water sampling*

Soil and water samples were collected in Vĩnh Long province from conventionally cultivated rice fields (VL-C) in April 2023 (10°01′47”N 106°11′00″E), and from certified organically cultivated fields (VL-O) in April 2023 and March 2024 (10°01′43”N 106°10′49″E). In Đồng Tháp (DT, 10°45′10.5”N 105°35′47.0″E) and An Giang (AG, 10°47′16.5”N 105°08′37.0″E) provinces, sampling was conducted in March 2024 (Fig. 1). Rice fields in An Giang were under organic management practices, although, these fields were not formally certified as organic and rice fields in Đồng Tháp were under a low pesticide input regime due to its proximity to a national park. Soil sampling in Vĩnh Long was carried out during two key periods: the vegetative phase of the cropping season (April 2023) and the fallow period (March 2024), allowing for seasonal comparison of pesticide residue dynamics. Water samples were collected in 500 mL PE plastic bottles and topsoil (0 to 15 cm) was sampled using a stainless steel auger (Standard Soil properties see

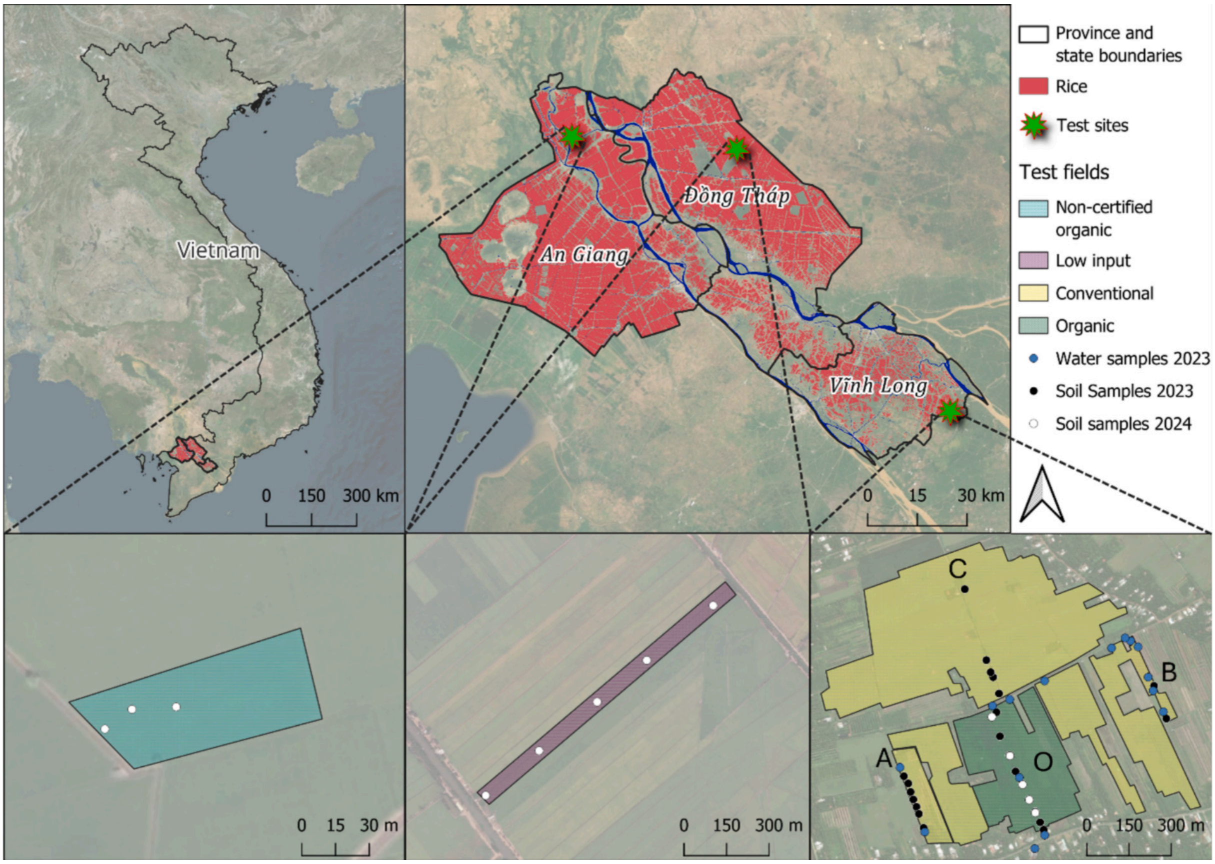


Fig. 1. Location of the study sites. Samples were taken at Dong Thap province (DT), An Giang province (AG) and Vinh Long province (VL-). In Vinh Long province, samples were taken from three different conventionally managed fields (-CA, -CB, -CC) and an organically managed field (—O). Different colors of the test field representing the different management systems (Kupfer et al., 2024).

Table S2). Each field was sampled as a single transect to achieve a representative sampling campaign across the site. To prevent pesticide degradation in soils after sampling, all soil samples were oven dried at 40 °C. Water samples were stored at 4 °C until pre-concentration and preservation on solid-phase extraction (SPE) cartridges. Subsequently, the SPE cartridges and soil samples were shipped to the Forschungszentrum Jülich GmbH in Germany for further analysis.

2.4. Sample preparation

All solvents and chemicals used were of LCMS grade and purchased from VWR, Darmstadt, Germany. For water sample preparation, 300 mL of water sample was first filtered through a glass fiber filter (pore size 0.7 μm; Whatman, Kent, UK), following a PVDF filter (pore size 0.22 μm; Merck Millipore®, MA, USA). The pesticides from the water samples were then extracted using an OASIS HLB cartridge (6 mL, 200 mg, Waters). SPE cartridges were pre-conditioned with 2 mL of methanol (MeOH) followed by 2 mL of deionized water. Subsequently, 300 mL of the water sample was passed through the cartridges at a flow rate of 5 mL·min^{-1}. For the cleaning step, 2 mL of a water:MeOH mixture (10:1, *v*/v) was applied. The cartridges were then dried under vacuum and stored for transport. After shipment to Germany, pesticides were eluted from the cartridges using 2 × 4 mL of MeOH and 2 × 4 mL of dichloromethane. The combined eluates were evaporated at 40 °C under a stream of nitrogen (N_2). The residue was reconstituted in 1 mL of a water:MeOH solution (3:1, *v*/v), filtered through a 0.22 μm PTFE membrane filter, and analyzed by LC-MS/MS.

Prior to the pesticide extraction from soil, the dried soil samples were crushed and sieved to ≤2 mm. Afterwards, an accelerated solvent extraction (ASE; Dionex 350, Thermo Scientific, MA, USA) was carried out based on a modified method proposed by Gan et al. (1999) using MeOH as extraction solvent. For the extraction, 6 g of dry soil was weight and mixed with diatomaceous earth and then packed into 20 mL stainless steel ASE vessels. The packed vessels were sealed at both ends with glass fiber filters (pore size 1.0 μm) and end caps. The diatomaceous earth was used to facilitate the solvent penetration through the soil matrix. The extraction was carried out under 100 °C, 1500 psi, and 15 min static time. The extract was finally filtered through a PVDF 0.45 μm filter, vaporized under N_2, resuspended in 1 mL water:MeOH (3:1, v/v), and finally centrifuged (Eppendorf Centrifuge 5417C) at 17500 RCF

Table 1

Studied pesticides, their chemical properties, recommended application rates and toxicity class.

Pesticides	Solubility[a]	Normalized soil sorption coefficient K_{oc} [a]	Half-life in soil DT_{50}[a]	GUS leaching potential index[a]	Recommended application dose[a]	Chemical Formula[a]	Substance group[a]	WHO Index[b]
	(mg L^{-1})	(mL g^{-1})	(days)	(–)	(g ha^{-1})			
Insecticides								
Chlorantraniliprole	0.88	362	597	3.51	30	$C_{18}H_{14}BrCl_2N_5O_2$	Diamide	U
Diethyltoluamide (DEET)	912	277	na	na	na	$C_{12}H_{17}NO$	Unclassified	III
Dimethoate	25,900	na	2.5	2.18	na	$C_5H_{12}NO_3PS_2$	Organophosphate/ Organothiophosphate	II
Fenobucarb	420	1068	18.5	1.23	na	$C_{12}H_{17}NO_2$	Carbamate	II
Imidacloprid	610	na	191	3.69	50	$C_9H_{10}ClN_5O_2$	Neonicotinoid	II
Thiamethoxam	4100	56.2	50	3.58	10	$C_8H_{10}ClN_5O_3S$	Neonicotinoid	II
Fungicides								
Azoxystrobin	6.7	589	78	3.1	100	$C_{22}H_{17}N_3O_5$	Strobilurin	U
Difenoconazole	15	na	133	0.89	45	$C_{19}H_{17}Cl_2N_3O_3$	Conazole	II
Edifenphos	56	1863	21	0.96	na	$C_{14}H_{15}O_2PS_2$	Organophosphate	Ib
Fenoxanil	30,700	576	2.5	0.49	96	$C_{15}H_{18}Cl_2N_2O_2$	Amide	na
Fluopyram	16	na	309	3.23	na	$C_{16}H_{11}ClF_6N_2O$	Benzamide/ Pyridine	III
Hexaconazole	18	1040	122	2.31	100	$C_{14}H_{17}Cl_2N_3O$	Triazole/ Conazole	III
Isoprothiolane	48.5	1352	78	1.64	480[d]	$C_{12}H_{18}O_4S_2$	Phosphorothiolate/ Dithiolane	II
Metalaxyl	8400	162	36	2.06	150	$C_{15}H_{21}NO$	Anilide/ Acylamino acid	II
Paclobutrazole	22.9	400	112	2.47	na	$C_{15}H_{20}ClN_3O$	Triazole	II
Propiconazole	150	1086	71.8	1.58	62.5	$C_{15}H_{17}Cl_2N_3O_2$	Triazole/ Conazole	II
Tebuconazole	36	na	63	1.86	86	$C_{16}H_{22}ClN_3O$	Triazole/ Conazole	II
Tricyclazole	596	169	67.9–78.9[c]	3.89	225	$C_9H_7N_3S$	Triazolobenzothiazole	II
Herbicides								
2,4-D	24,300	39.3	4.4	3.82	na	$C_8H_6Cl_2O_3$	Phenoxyacetic	II
Ametryn	200	316	37	0.46	na	$C_9H_{17}N_5S$	Triazine	II
Atrazine	35	100	75	2.57	80	$C_8H_{14}ClN_5$	Triazine/ Chlorotriazine	III
Flumetsulam	5650	28	45	4.22	na	$C_{12}H_9F_2N_5O_2S$	Sulfonanilide/ Triazolopyrimidine	U
Metalochlor	360,000	17	325	6.88	na	$C_{15}H_{21}NO_4$	Unclassified	III
Pretilachlor	500	na	30	na	396	$C_{17}H_{26}ClNO_2$	Chloroacetanilide	U
Pyrazosulfuron-ethyl	14.5	154	15	2.13	na	$C_{14}H_{18}N_6O_7S$	Sulfonylurea/ Pyrazole	U
Quinclorac	0.065	50	450	6.29	17.8	$C_{10}H_5Cl_2NO_2$	Quinolinecarboxyli	III
Molluscicides								
Niclosamide	5	3112	na	na	210	$C_{13}H_8Cl_2N_2O_4$	Chloronitrophenol	U

[a] Source: PPDB (Pesticide properties database, https://sitem.herts.ac.uk/aeru/ppdb/).

[b] WHO toxicity classes: Class Ib: highly hazardous, Class II: moderately hazardous, Class III: slightly hazardous, U: unlikely to present acute hazard (WHO, World Health Organization).

[c] Saini et al. (2025).

[d] Braun et al. (2019).

for 15 min. Afterwards, the supernatant was filtered through a PTFE filter (pore size 0.22 μm) and further analyzed by LC-MS/MS.

2.5. Pesticide analysis

To assess the pesticide pollution, target pesticides were selected based on 1) common used pesticides identified through the farmers interviews and pesticide packages found on the rice fields, 2) a target screening of pesticides via LC-MS/MS using the Xevo Quanpedia (Waters) data base, which contains the information of 750 widely used pesticides, and 3) physico-chemical properties, including solubility in water, soil sorption, and soil degradation half-life, GUS leaching potential index, and its ecotoxicological relevance (Table 1). These factors collectively influence the substance's behavior, mobility, persistence, and potential toxic effects within ecosystems. In total, 32 pesticides were selected for quantitative analysis in this study. Pesticide standards with a purity >97% were purchased from LGC Standards (Wesel, Germany), VWR or Biomol (Hamburg, Germany) for pesticide quantification (Recovery see Table S3). Standard pesticide solutions were prepared in water:MeOH (3:1, *v*/v) and kept dark at −20 °C. Pesticide analyses were carried out on a Waters ACQUITY UPLC system (binary pump, autosampler) coupled to a Waters Xevo TQ-S triple quadrupole mass spectrometer (Waters Technologies Corp., MA, USA) driven in the positive and negative electrospray ionization (ESI) mode. Sample injections were 10 μL and the chromatographic separation was achieved on a reversed-phase C-18 column (Nucleoshell RP18, Macherey-Nagel (100 mm × 4.6 mm, 2.7 μm)). The column oven temperature was 40 °C. Gradient elution was performed at a flow rate of 1.0 mL min^{-1}. Gradient conditions started at 2% mobile phase B and increase to 100% over 30 min, then returned to 2% at 30.1 min and held for 4 min. The total run time was 34 min with a post-run of 4 min, where the column was washed with 98% mobile phase A and 2% mobile phase B. For each pesticide, monitoring conditions were individually optimized for the multiple reaction monitoring (MRM) mode, including the selection of precursor and product ions, collision energy, cone voltage, and retention time windows (for details see Table S4). Furthermore, the capillary voltage was set to 2.5 kV (ESI +) or 2.0 kV (ESI -), the gas flow to 1000 L hr^{-1} and desolvation temperature at 600 °C.

2.6. Statistical analysis

All statistical analyses were performed using R version 4.4.0 (R Core Team, 2024). To assess regional differences in the use of plant protection active substances reported by farmers, a chi-square test of independence was performed. This statistical test evaluates whether the observed frequencies of individual active substances across provinces significantly deviate from the expected frequencies under the assumption of a uniform distribution. The test requires that at least 80% of cells have expected frequencies of at least 5, and that no expected frequency is less than 1. Since these assumptions were not fully met in the present data, only active ingredients that were named at least 5% by the farmers of at least one province were considered. To identify which active ingredients and provinces contributed most to the overall differences, standardized residuals from the chi-squared test were examined. Residuals with an absolute value greater than 2 (Table S5) were interpreted as statistically conspicuous.

To analyze differences in organic and conventional rice cultivation, the sum of all detected pesticide concentrations per sample was calculated to determine the total pesticide pollution for each field and cultivation group. Differences in total pesticide pollution among the fields and cultivation groups were assessed using the non-parametric Kruskal-Wallis test, as the data did not meet the assumptions of normality (Shapiro-Wilk test, $p < 0.05$, Table S6). In this analysis, the dependent variable was the total pesticide concentration per sample, while the independent variable was the cultivation group (i.e., field management type). A significance level of $p < 0.05$ was applied.

3. Results and discussion

3.1. Farmer survey

The interviews conducted with 155 famers in An Giang, Đồng Tháp, and Vĩnh Long provinces documented 640 pesticide products used by farmers practicing conventional rice farming. The documented labels of the pesticide packages and reported brand names were checked for their active ingredients. In total, 80 different active ingredients were identified as single compound applications or as mixed ingredient products. The active ingredients were categorized into the groups of herbicides, fungicides, bactericides, and molluscicides. Insecticides and acaricides were treated as one category since some active ingredients are effective against both insects and mites or ticks, which are targeted by acaricides. With around one third respectively (Fig. 2), the majority of active ingredients reported belong to the categories of fungicides, insecticides, and herbicides. In contrast, bactericides and molluscicides were less frequently mentioned by farmers. Within Vĩnh Long only two instances of molluscicide and eight of bactericide use were recorded, while in Đồng Tháp seven and nine mentions were documented, respectively.

Fig. 3 shows the proportional distribution of active ingredients reported across the three provinces for the pesticide categories of fungicides, herbicides, and insecticides. Only substances reported in more than 5% of the entire records per province are shown. This threshold ensures that the analysis focuses on commonly reported active ingredients, and therefore, reduces noise from infrequent entries with limited impact on overall trends.

Five active ingredients were frequently reported as herbicides, alongside Fenclorim, which is used as a herbicide safener. Fenclorim was particularly applied in combination with Pretilachlor to protect rice crops from potential injury caused by potent herbicides such as Pretilachlor. Statistical analysis using a chi-squared test of independence indicated that the overall distribution of herbicide active ingredients was largely similar across provinces, with one notable exception of the active ingredient of Cyhalofop-butyl, which was used significantly more frequently in Đồng Tháp than in the other provinces, as indicated by the standardized residuals. In An Giang and Đồng Tháp, Butachlor, with 40.4 and 34.3% respectively, was the most frequently reported active ingredient. In Vĩnh Long, both Butachlor and Propanil were reported with equal frequency of 31.6% (detailed information see Fig. S1). In general, the three active ingredients identified as the primary herbicides across the three provinces were Butachlor, Propanil, and Pretilachlor, with Pretilachlor reported at 17.7% in An Giang, 15.7% in Đồng Tháp, and 21.1% in Vĩnh Long province. For the fungicide category, ten active ingredients were identified as predominating. In all three provinces, Tricyclazole was the most commonly reported fungicide, accounting for 33.3% in Đồng Tháp, 20.7% in An Giang, and 18% in Vĩnh Long province (detailed information see Fig. S2). However, statistical analysis using a chi-squared test of independence confirmed that the distribution

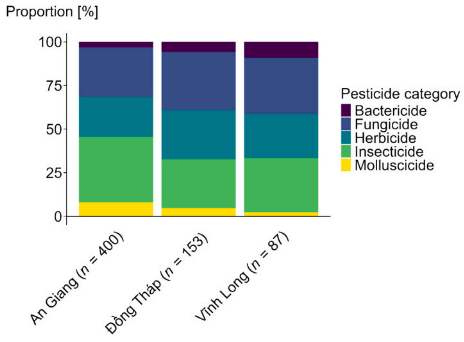


Fig. 2. Reported pesticides by category in An Giang, Đồng Tháp, and Vĩnh Long province. Number of reporting (n) of each active substance were quantified without regarding dosage or quantities applied.

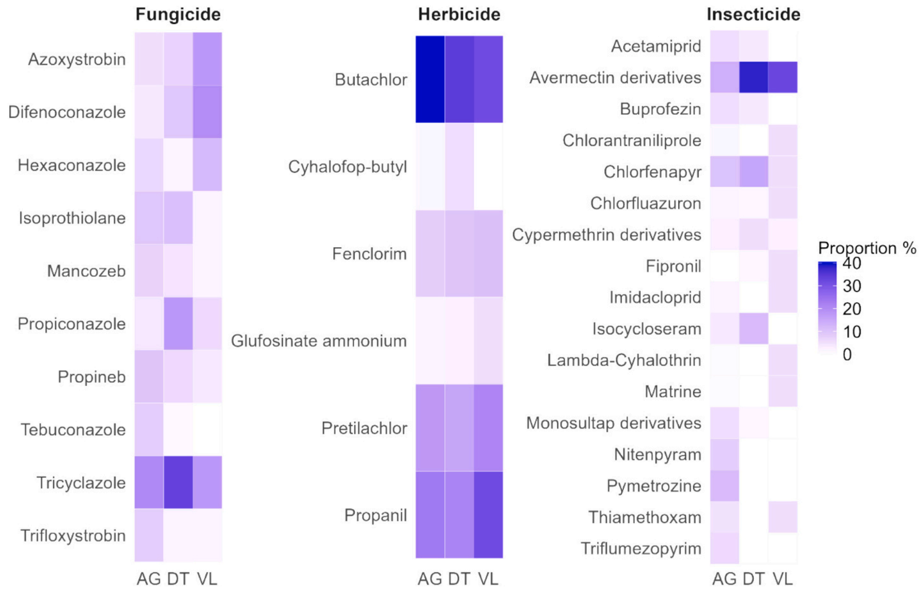


Fig. 3. Proportional distribution of pesticide active ingredients reported through farmer interviews and pesticide package labels in An Giang (AG), Đồng Tháp (DT), and Vĩnh Long (VL) province. Only active ingredients representing ≥5% of total reports per province are shown.

of fungicide active ingredients differed significantly between provinces ($p < 0.05$; see Table S5 for standardized residuals). Analysis of standardized residuals indicated that Difenoconazole (20%) and Azoxystrobin (19%) were reported significantly more frequently in Vĩnh Long province, while Propiconazole (17.9%) was notably more reported in Đồng Tháp province. Tebuconazole and Trifloxystrobin were most prominent in An Giang, where both substances accounted for 8.5% of the reported active ingredients. Packages frequently contained combined formulations of two or three of the ten most prevalent active ingredients. In the insecticide category, including acaricides, 17 active ingredients were reported above the 5% threshold. Statistical analysis demonstrated that the distribution of insecticide active ingredients varied significantly between provinces ($p < 0.05$). The group of Avermectin Derivatives (including Abamectin, Abamectin Benzoate, and Emamectin Benzoate) was particularly prominent across all three provinces (13.8% in An Giang, 38.5% in Đồng Tháp, 32.4% in Vĩnh Long, more detailed information see Fig. S3). However, standardized statistical residuals (see Table S5 for standardized residuals) showed, that Avermectin Derivatives were used significantly more frequently in Đồng Tháp and Vĩnh Long province. Avermectin compounds, such as Abamectin, are natural products derived from the soil bacterium *Streptomyces avermitilis* and are widely used as insecticides and acaricides (Copping and Menn, 2000). Produced by microbial fermentation, they meet Vietnam's legal definition of biopesticide products with active ingredients from microorganisms, plants, or animals (Law No. 41/2013/QH13) and continue to be officially classified and registered as a biopesticide in the country (Nguyen, 2021; Socialist Republic of Vietnam, 2013). This status persists despite its classification by the World Health Organization as a highly hazardous pesticide (Class Ib) due to its neurotoxic effects (WHO, 2020). This dual classification highlights the ongoing regulatory challenge of balancing biological origin with toxicological risk in pesticide policy (Van Hoi et al., 2013). Additionally, standardized residuals indicated that Pymetrozine was significantly more often mentioned by farmers in An Giang province, while Isocycloseram was notably more often mentioned from farmers in Đồng Tháp province. Generally, a broad range of active ingredients were mentioned across all provinces. Insecticidal active ingredients were also often detected in mixtures than as individual compounds.

To gain a deeper understanding of pest pressure and management strategies in the studied regions, the reported active ingredients were classified into functional categories based on their primary target organisms and modes of action. This categorization enables a more nuanced interpretation of pesticide use patterns and provides insights into the specific pest challenges faced by farmers in each province. Analysis of usage patterns of herbicides revealed clear trends regarding both selectivity and application timing. Selective herbicides, particularly Butachlor, Propanil, and Pretilachlor, were by far the most commonly reported in all regions. These herbicides are designed to target specific weed groups, primarily grasses and some broadleaf weeds, while minimizing phytotoxicity to rice. Non-selective herbicides, such as Glufosinate-ammonium, were used only to a minor extent. Regarding application timing, pre-emergence herbicides, especially Butachlor and Pretilachlor, dominated across all provinces, indicating a widespread strategy of early weed control to suppress competition during the critical initial growth stages of rice. Post-emergence herbicides, such as Propanil and Cyhalofop-butyl, were also used, presumably as follow-up treatments or in combination with pre-emergence applications. In summary, all provinces showed a clear preference for selective herbicides and early (pre-emergence) application strategies. The main difference was a higher trend on post-emergence herbicides in Vĩnh Long, whereas Đồng Tháp and An Giang favored a greater use of pre-emergence applications. These findings reflect a general trend of targeted weed management in rice cultivation across the study areas.

To explore regional patterns in fungal disease management, the reported use of fungicide active ingredients was categorized by their fungicide activity spectrum and type of systemicity (Fig. 4). Particularly in An Giang and Đồng Tháp, fungicides with a preventative spectrum were commonly reported, while active ingredients reported in Vĩnh Long province showed a stronger emphasis on both curative and preventative properties. For all three provinces, systemic fungicides were the most frequently reported active ingredients, with the highest values observed in Đồng Tháp, followed closely by Vĩnh Long and An Giang. This highlights a general preference for active ingredients that are translocated within the plant, offering internal protection. Usage of systemic/translaminar, contact and locally systemic fungicides was consistently lower in all three provinces. Over the past years, rice blast is consistently reported as the most concerning fungal disease in the Mekong Delta. The region's tropical climate strongly favors fungal development, with prolonged wet seasons contributing to yield losses of up to 20%. These conditions pose a serious threat to food security and the livelihoods of rice farmers (Nguyen et al., 2021; Phi, 2023; Thi Lang et al., 2010). However, extensive chemical control presents major

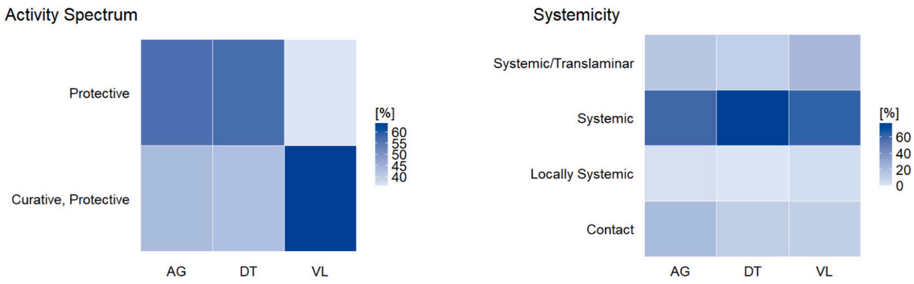


Fig. 4. Classification of fungicidal active substances by activity spectrum and systemicity across the three provinces An Giang (AG), Đồng Tháp (DT), and Vĩnh Long (VL). Each active ingredient was categorized according to its use as either preventive or both preventive and curative, and subsequently classified based on its systemic properties.

challenges, including the development of fungicide resistance in pathogens, especially of systemic fungicides, and the negative environmental impacts of multiple fungicide application (Brent and Hollomon, 2007). For instance, Tricyclazole, one of the most commonly reported fungicides in rice cultivation, is often applied preventively and has a soil half-life ranging from 67.9 to 78.9 days in clay loam soil (Saini et al., 2025) and a mean half-life in paddy water of 11.8 days (Phong et al., 2009), raising concerns about environmental persistence. Studies have shown, that combining different fungicides can improve efficacy, and multiple applications tend to reduce disease incidence more effectively than single treatments (Phi, 2023). However, this repeated use further amplifies concerns regarding chemical buildup and resistance development. A potential approach offering a more sustainable alternative to chemical-based disease management involves the development of resistant rice varieties combined with the use of biological control agents such as *Streptomyces* spp. (Law et al., 2017; Phi, 2023). To explore regional patterns in insect pest management, the reported use of insecticidal active ingredients was analyzed by the insect feeding behavior of their primary target pests (Pathak and Khan, 1994).

Fig. 5 highlights the regional variation across An Giang, Đồng Tháp, and Vĩnh Long province. Across all locations, sap-sucking pests were identified as the most frequently targeted group, with the highest frequency of insecticide use observed in An Giang province. A similar, albeit slightly lower, emphasis on the control of sap-sucking pests was also observed in Đồng Tháp and Vĩnh Long. This suggests that sap-sucking insects such as planthoppers, aphids, and leafhoppers represent a major pest challenge in this region. These results align with previous studies emphasizing that rice planthoppers are still a major concern in the Mekong Delta. Sap-sucking pests are not only causing direct feeding damage but also transmit viruses such as rice grassy stunt virus, leading to significant yield losses (Cohen et al., 2008; Yuen et al., 2021). The emergence of planthoppers as major pests in the 1960s and 1970s has been closely linked to agricultural intensification, underscoring the role of modern farm management practices in promoting population build-up and yield losses in tropical rice systems (Savary et al., 2012). Between 2005 and 2008, An Giang and Đồng Tháp provinces were severely affected by brown planthopper outbreaks, which, together with the associated virulent disease, led to significant yield losses, impacting approximately 50% of the cultivated rice areas. (Yuen et al., 2021). In addition, widespread insecticide use has been shown to disrupt natural enemy communities and induce resurgence of hopper populations (Berg et al., 2025; Savary et al., 2012). A recent study showed, that sublethal doses of Avermectins can stimulate reproduction in brown planthoppers enhancing pest resurgence after treatment (Gao et al., 2025), but also Imidacloprid is associated with increased rates of resistance development and pest resurgence in brown planthoppers (Azzam et al., 2011). These results ultimately undermine the need of sustainable pest control efforts. Mining/boring pests, such as stem borers, leaf folders, and leaf miners were the second most commonly identified targeted pest group across all provinces, with similar levels observed in Đồng Tháp and Vĩnh Long province. These results point to a consistent need to manage internally feeding pests such as stem borers and leaf miners (Yuen et al., 2021). Leaf feeders, including caterpillars, armyworms, grasshoppers, and beetles, were generally targeted at lower frequencies across all provinces, with only Vĩnh Long showing a modestly higher use of insecticides against this group compared to An Giang and Đồng Tháp. This might reflect either a higher prevalence of foliar-feeding pests in Vĩnh Long or a shift in treatment strategies. Grain feeders were the least frequently targeted pest group in all provinces, indicating that insects feeding on developing rice grains, such as stink bugs or rice ear-head bugs, were either of limited concern during the survey period or effectively managed with broad-spectrum insecticides not specific to this group.

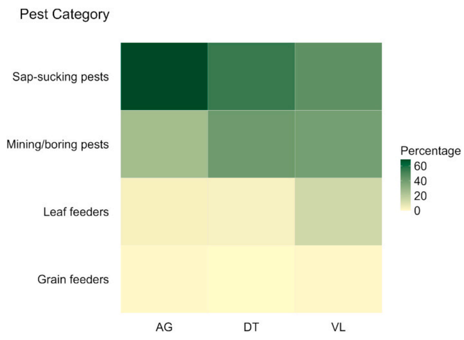
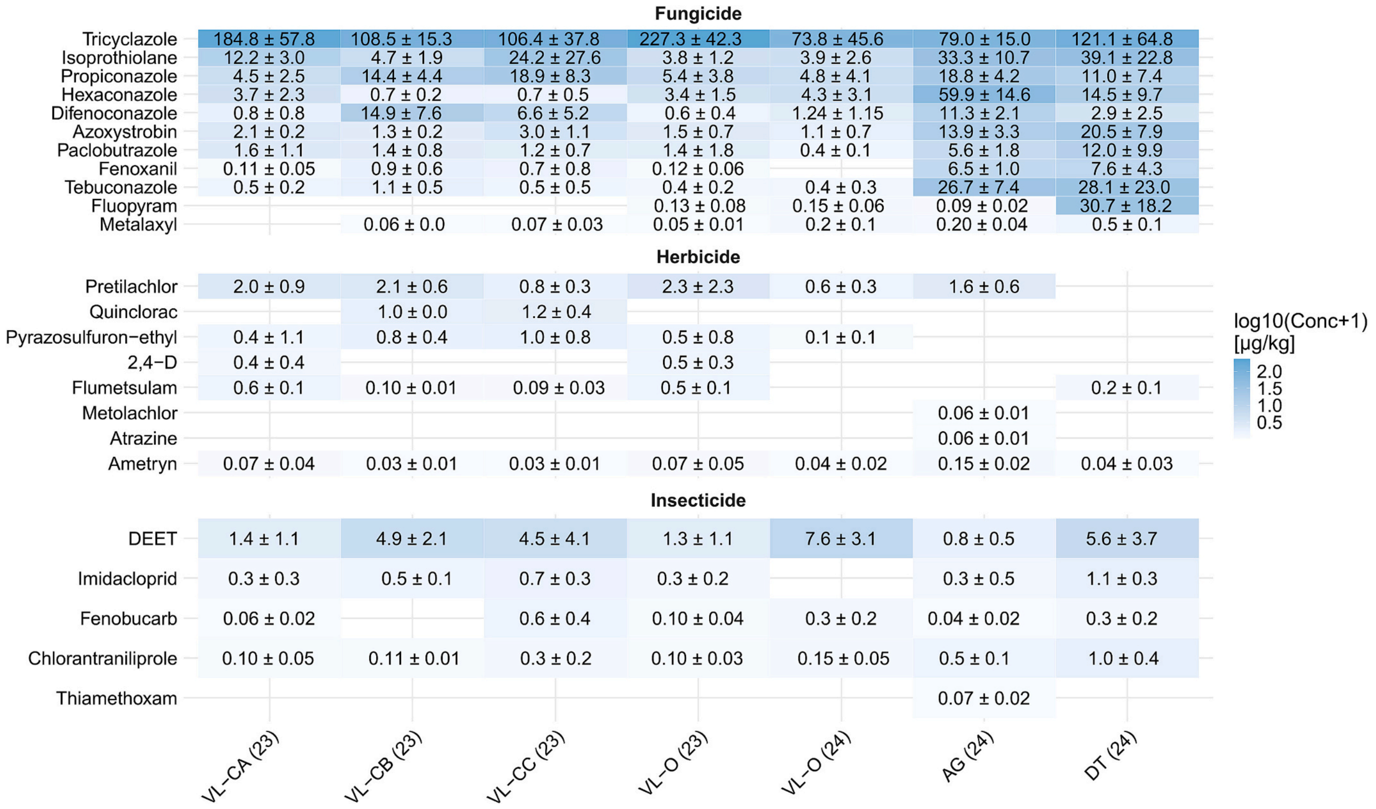


Fig. 5. Insect pest pressure identified though defining pest categories based on the insect feeding habit, in relation to insecticide usage patterns across the provinces An Giang (AG), Đồng Tháp (DT), and Vĩnh Long (VL). Each active ingredient was assigned to one or more pest groups based on the feeding behavior of its target organisms. When multiple pest groups were associated with a single active ingredient, its reported use frequency was evenly divided among them. Values represent the aggregated, weighted percentage of insecticide use per pest group and province.

3.2. *Pesticide residue analysis in soil and water samples*

In total, 24 of the 32 analyzed pesticides consisting of 13 fungicides, 5 herbicides, 8 insecticides and traces of one molluscicide were detected in the topsoil (0–10 cm) from one field respectively in An Giang and Đồng Tháp province, and 4 fields in Vĩnh Long province (Fig. 6). In surface water samples, taken from standing water on rice fields and from irrigation cannels, a total of 28 of 31 analyzed pesticides (11 fungicides, 9 herbicides, 6 insecticides, 2 molluscicides) were detected. Following targeted screening, selected pesticides were quantified for further analysis. Summing up all detected concentrations of pesticide residues, a mean sum pesticide concentration of 178.3 μg kg^{-1} was found in soil samples from Vĩnh Long province, 258.9 μg kg^{-1} in soil samples from Đồng Tháp province, and even 296.4 μg kg^{-1} in soil samples from An Giang province. Overall, the pesticide residues detected in soil samples from the studied provinces aligned with the expected ones derived from farmer survey reports. In general, fungicide residues were prevalent in



	VL–CA (23)	VL–CB (23)	VL–CC (23)	VL–O (23)	VL–O (24)	AG (24)	DT (24)
Fungicide							
Tricyclazole	184.8 ± 57.8	108.5 ± 15.3	106.4 ± 37.8	227.3 ± 42.3	73.8 ± 45.6	79.0 ± 15.0	121.1 ± 64.8
Isoprothiolane	12.2 ± 3.0	4.7 ± 1.9	24.2 ± 27.6	3.8 ± 1.2	3.9 ± 2.6	33.3 ± 10.7	39.1 ± 22.8
Propiconazole	4.5 ± 2.5	14.4 ± 4.4	18.9 ± 8.3	5.4 ± 3.8	4.8 ± 4.1	18.8 ± 4.2	11.0 ± 7.4
Hexaconazole	3.7 ± 2.3	0.7 ± 0.2	0.7 ± 0.5	3.4 ± 1.5	4.3 ± 3.1	59.9 ± 14.6	14.5 ± 9.7
Difenoconazole	0.8 ± 0.8	14.9 ± 7.6	6.6 ± 5.2	0.6 ± 0.4	1.24 ± 1.15	11.3 ± 2.1	2.9 ± 2.5
Azoxystrobin	2.1 ± 0.2	1.3 ± 0.2	3.0 ± 1.1	1.5 ± 0.7	1.1 ± 0.7	13.9 ± 3.3	20.5 ± 7.9
Paclobutrazole	1.6 ± 1.1	1.4 ± 0.8	1.2 ± 0.7	1.4 ± 1.8	0.4 ± 0.1	5.6 ± 1.8	12.0 ± 9.9
Fenoxanil	0.11 ± 0.05	0.9 ± 0.6	0.7 ± 0.8	0.12 ± 0.06		6.5 ± 1.0	7.6 ± 4.3
Tebuconazole	0.5 ± 0.2	1.1 ± 0.5	0.5 ± 0.5	0.4 ± 0.2	0.4 ± 0.3	26.7 ± 7.4	28.1 ± 23.0
Fluopyram				0.13 ± 0.08	0.15 ± 0.06	0.09 ± 0.02	30.7 ± 18.2
Metalaxyl		0.06 ± 0.0	0.07 ± 0.03	0.05 ± 0.01	0.2 ± 0.1	0.20 ± 0.04	0.5 ± 0.1
Herbicide							
Pretilachlor	2.0 ± 0.9	2.1 ± 0.6	0.8 ± 0.3	2.3 ± 2.3	0.6 ± 0.3	1.6 ± 0.6	
Quinclorac		1.0 ± 0.0	1.2 ± 0.4				
Pyrazosulfuron−ethyl	0.4 ± 1.1	0.8 ± 0.4	1.0 ± 0.8	0.5 ± 0.8	0.1 ± 0.1		
2,4−D	0.4 ± 0.4			0.5 ± 0.3			
Flumetsulam	0.6 ± 0.1	0.10 ± 0.01	0.09 ± 0.03	0.5 ± 0.1			0.2 ± 0.1
Metolachlor						0.06 ± 0.01	
Atrazine						0.06 ± 0.01	
Ametryn	0.07 ± 0.04	0.03 ± 0.01	0.03 ± 0.01	0.07 ± 0.05	0.04 ± 0.02	0.15 ± 0.02	0.04 ± 0.03
Insecticide							
DEET	1.4 ± 1.1	4.9 ± 2.1	4.5 ± 4.1	1.3 ± 1.1	7.6 ± 3.1	0.8 ± 0.5	5.6 ± 3.7
Imidacloprid	0.3 ± 0.3	0.5 ± 0.1	0.7 ± 0.3	0.3 ± 0.2		0.3 ± 0.5	1.1 ± 0.3
Fenobucarb	0.06 ± 0.02		0.6 ± 0.4	0.10 ± 0.04	0.3 ± 0.2	0.04 ± 0.02	0.3 ± 0.2
Chlorantraniliprole	0.10 ± 0.05	0.11 ± 0.01	0.3 ± 0.2	0.10 ± 0.03	0.15 ± 0.05	0.5 ± 0.1	1.0 ± 0.4
Thiamethoxam						0.07 ± 0.02	

Fig. 6. Detected pesticide residues of the seven sampling sites in An Giang (AG), Đồng Tháp (DT), and Vĩnh Long (VL-) province. The sampling year is assigned to the respective regions. Results are shown as fungicide, herbicide, and insecticide mean concentrations (μg kg^{-1}) in soil (dry matter) of different fields and cultivation systems (non-certified organic: AG ($n = 6$), low input: DT ($n = 10$), conventional: VL-CA ($n = 16$), VL-CB ($n = 6$), VL-CC ($n = 7$), and organic cultivation: VL-O (23) ($n = 18$), VL-O (24) ($n = 9$). For statistical evaluation, non-quantified pesticides were calculated as routine limit of quantification (RLOQ) and non-detected pesticides were calculated as RLOQ * 0.5. Rice fields in which all substances were either non-detectable or below the quantification limit were excluded from the analysis.

the soil samples, with Tricyclazole, emerging as both the most commonly reported by farmers and the compound detected at the highest concentrations in soils across the three provinces, with both, the highest peak concentration 283.6 μg kg^{-1} and the highest mean concentration of 227.3 μg kg^{-1} among all detected compounds (See Supplementary Table S7 and Table S8). Tricyclazole (5-methyl-1,2,4-triazolo(3,4-b) benzothiazole) is recognized as one of the most widely applied fungicides in Asian countries controlling rice blast disease (Jeong et al., 2012). Its consistent detection in soils is likely a consequence of its recommended high application rate (225 g ha^{-1}), frequent use (two applications per growing season (Elamawi et al., 2018)), and long half-life (DT_{50} 67.9–78.9 days, highly depending on the soil types and organic amendments (Saini et al., 2025). Other research in Vietnam documented Tricyclazole residues also in rice samples from organically managed fields, with concentrations ranging from 31 μg kg^{-1} in 2019 to 21 μg kg^{-1} in 2021, although, only a single soil sample was tested, showing a residue level of 70 μg kg^{-1} (Nguyen et al., 2022). These findings underscore the need for comprehensive monitoring of Tricyclazole pollution especially in organic rice production systems, as to date data remain sparse. Our data also reveals, that high Tricyclazole residues, of up to 283.6 μg kg^{-1} (Fig. 6), can occur in soils from organic rice cultivation systems, which might cause serious problems for product safety. As mentioned, the persistence of Tricyclazole in the environment is likely caused by its long half-life leading to accumulation in both, the paddy soils but also in the rice plants. Additionally, the high concentrations found in the organic production system leads to the question of origin. As spray drift from adjacent conventional farmland can be largely excluded, the only transportation pathway can be via the irrigation water (fully dissolved or via the sediments (bound fraction) transported into the fields. As there has been no clear trend in the concentrations measured along the transect within the organic or conventional production system from the irrigation channel to the points far away from the water inlet and as the water is mainly pumped from the irrigation channel, the pollution by Tricyclazole is most likely via the dissolved phase.

As Tricyclazole pollution raises concern not only in Vietnam but also in Europe, the EU regulatory authorities conducted a detailed risk assessment of Tricyclazole and identified substantial, unresolved concerns and data gaps regarding its environmental and human health effects, specifically citing its potential genotoxicity, carcinogenicity, endocrine-disrupting properties, and risks of environmental contamination (EFSA, 2015). Consequently, regulatory restrictions, including a ban of Tricyclazole in the European Union, were implemented to mitigate these risks Commission Implementing Regulation (EU) 2016/1826 (2016). As a result, according to Regulation (EC) No 396/2005 the established maximum residue limit for Tricyclazole in rice in the EU was set at 0.01 mg kg^{-1}, underscoring the need for ongoing monitoring of residues and prudent management of Tricyclazole in rice production areas (European Parliament and the Council of the European Union, 2005). This holds especially in regions like the Mekong Delta, where limited data suggest, that residue levels exceed the EFSA's maximum residue limit (EFSA, 2020). Consistent with earlier research conducted in Đồng Tháp province documenting Isoprothiolane residues in surface waters with peak concentrations of 11.24 μg L^{-1} (Van Toan et al., 2013) and 8.49 μg L^{-1} (Chau et al., 2015), as well as average concentrations of 182.0 μg kg^{-1} in soils and sediments (Van Toan et al., 2013), our study similarly detected Isoprothiolane residues in paddy soils. Specifically, peak concentrations reached 92.2 μg kg^{-1} in soils sampled in Đồng Tháp and 2.1 μg L^{-1} in the irrigation water in Vĩnh Long (see Table S9). Isoprothiolane was also reported in rice samples in the study of C. T.

Nguyen et al. (2022). However, the findings do not exceed the maximum residue limit of any regulation to this point. Our findings correspond with earlier reports attributing the widespread occurrence of Isoprothiolane in rice cultivation systems to its physicochemical characteristics, high recommended application rate of 480 g ha^{-1}, and frequent use for controlling rice blast disease (Braun et al., 2019). Furthermore, the notable environmental persistence of Isoprothiolane, evidenced by its relatively long half-life (DT_{50} up to 320 days), likely contributes to its sustained presence in soil environments. Generally, the majority of detected fungicides corresponded well with farmer-reported usage. However, an exception was observed for Fluopyram with concentrations up to 71.7 μg kg^{-1} in the soil, a fungicide frequently applied to soybeans, cotton, and vegetables but not rice. Its presence in the soils contrasted due to its usage with survey responses, indicating possible cross-contamination through alternative sources such as the irrigation water. Furthermore, across the three provinces several other fungicides with peak concentrations of Propiconazole (32.0 μg kg^{-1}, Vĩnh Long), Hexaconazole (85.7 μg kg^{-1}, An Giang), Difenoconazole (25.6 μg kg^{-1}, Vĩnh Long), Azoxystrobin (33.9 μg kg^{-1}, Đồng Tháp), Paclobutrazole (34.5 μg kg^{-1}, Đồng Tháp), Tebuconazole (82.2 μg kg^{-1}, Đồng Tháp), Fenoxanil (15.2 μg kg^{-1}, Đồng Tháp) and traces of Metalaxyl (0.63 μg kg^{-1}, Đồng Tháp) were detected. The measured fungicide concentrations of our soil samples fall within the range reported by C. T. Nguyen et al. (2022), supporting consistency between our data and previous pesticide residue assessments in the region.

A similar residue pattern was observed for herbicides in the study area. Pretilachlor, a widely used herbicide in rice cultivation, was detected at the highest concentrations among herbicides across the three provinces. Peak concentrations of Pretilachlor reached 8.36 μg kg^{-1} in soils and 0.05 μg L^{-1} in water samples collected from organic fields in Vĩnh Long. These soil residue levels represent notable detection since previous studies in the Mekong Delta have typically reported Pretilachlor primarily in water bodies rather than soils. For example, Chau et al. (2015) reported peak Pretilachlor concentrations of 0.85 μg L^{-1} in the water of an irrigation canal, while Van Toan et al. (2013) found concentrations of 0.21 to 1.05 μg L^{-1}in surface waters, but both studies did not report Pretilachlor residues in soils. This suggests that while Pretilachlor contamination of surface waters is well-documented, documentation of its presence and accumulation in rice paddy soils is scarce within this region. In addition, trace levels of Flumetsulam (max. 0.79 μg kg^{-1}, Vĩnh Long), Atrazine (max. 0.08 μg kg^{-1}, An Giang), and Ametryn (max. 0.18 μg kg^{-1}, Vĩnh Long) were detected, whereby these herbicides are typically not used in rice production systems. 2,4-Dichlorophenoxyacetic acid (2,4-D), a herbicide commonly used in rice farming, was detected at concentrations up to 1.55 μg kg^{-1} in soil. Although its use was not mentioned in farmer interviews, similar mean concentrations were found in paddy water of both conventionally managed (0.212 μg L^{-1}) and organically managed fields (0.086 μg L^{-1}), as well as in the irrigation channel water (0.185 μg L^{-1}). This suggests possible unreported usage or cross-contamination from other agricultural production systems. When comparing these environmental concentrations with Vietnamese regulations, the national technical regulation QCVN 38:2011/BTNMT (Ministry of Natural Resources and Environment (MONRE), 2011) sets a threshold of 200 μg L^{-1} for 2,4-D in surface water intended for the protection of aquatic life. The concentrations detected in all sampled waters are well below this national regulatory limit, thus complying with Vietnamese standards. However, in the context of the European Union (EU) regulations, the thresholds are significantly stricter. Under the EU Water Framework Directive on environmental quality standards in the field of water policy (Directive 2008/105/EC, amended by 2013/39/EU, European Union (2013)), the maximum permissible concentration for 2,4-D in surface water is set at 0.1 μg L^{-1} for individual pesticides, and the combined threshold for the sum of all pesticides is 0.5 μg L^{-1} in surface water. In light of these EU standards, the concentrations of 2,4-D detected in conventional paddy fields (0.212 μg L^{-1}) and irrigation water (0.185 μg L^{-1}) exceed the individual pesticide limit, thus not meeting EU regulatory requirements. Moreover, the average sum of pesticide residues was 2.7 μg L^{-1} in irrigation water and 1.2 μg L^{-1} in organically managed fields, both surpassing the EU's aggregate limit of 0.5 μg L^{-1}. While the timing of pesticide applications in conventional fields is unknown, complicating direct assessment of compliance in these waters, the detection of such pesticide concentrations in irrigation water and organically managed fields is particularly problematic. The irrigation water is also used for organic rice production, where such residue levels should ideally be absent or negligible. Since Vietnam currently lacks regulations setting aggregate thresholds for pesticides in surface water, comparing the detected sums with EU standards reveals that the pesticide levels found are substantially higher than would be permissible in Europe. This discrepancy highlights a need for enhanced regulatory frameworks, improved monitoring, and stringent measures to prevent cross-contamination, especially for irrigation sources used in organic agriculture. Regarding insecticide residues, compounds such as Imidacloprid, Chlorantraniliprole, and Thiamethoxam, regularly used in rice cultivation, with concentrations up to 1.48 μg kg^{-1}, were found in the soil samples, aligning with farmer-reported practices. While trace levels of Fenobucarb of up to 0.92 μg kg^{-1} were detected in soils, this insecticide, commonly used in rice farming, was not mentioned by any farmer interviewed. However, Chau et al. (2015) reported peak Fenobucarb concentrations of 2.32 μg L^{-1} in waters analyzed. Interestingly, the highest insecticide concentrations were found for N,N-diethyl-m-toluamide (DEET) with up to 13.21 μg kg^{-1}, a compound predominantly utilized as an insect repellent and not approved for agricultural applications, indicating potential sources unrelated to direct agronomic use (Zeiger et al., 1999). Research on DEET pollution in Vietnam is currently scarce, with little to no published studies specifically addressing its presence in soils or water bodies, including those in the Mekong Delta region. Nevertheless, DEET is widely used worldwide as a personal insect repellent and can enter aquatic and terrestrial environments through domestic wastewater discharge and recreational preactivities. The detection of DEET residues in the Mekong Delta soils therefore likely reflects the transport via the irrigation water, whereby the source can be linked to human usage rather than agricultural application. Despite this occurrence, there remains a significant gap in understanding the environmental distribution, fate, and potential ecological impacts of DEET in Vietnam.

To assess the spatial variation of pesticide residues in neighboring rice fields in Vĩnh Long province, soil samples were collected from three conventionally and one organically managed rice field (Fig. 1). Additionally, 15 water samples were collected as previous described. No significant differences in the total concentrations of pesticide residues in soils were observed among the four fields in Vĩnh Long province ($p > 0.05$; see Table S6). Notably, pesticide residues were also detected in the organically managed rice field. This finding is of particular concern, as certified organic farming, under frameworks such as Council Regulation (EC) No 834//2007 (2007) on Organic Production in the EU, the USDA National Organic Program (7CFR Part 205) of the United States Department of Agriculture (USDA) (2000), and the Japanese Agricultural Standards (JAS) for Organic Agricultural Products and Processed Foods, (Ministery of Agriculture, F. and F. (Japan), 2000), not only prohibits the use but also the presence of synthetic pesticide residues in the fields. The pesticide pollution of the organically managed field may result from geographical factors, including the contamination from adjacent conventional managed fields and the use of shared irrigation systems, which can facilitate pesticide transport from those fields to the organically ones through runoff and leaching, spray drift, or backflow within the irrigation networks (Schleiffer and Speiser, 2022). For instance, cross-connections in irrigation systems allow the pesticide transfer between adjacent fields, while runoff and lateral subsurface flow promote pesticide movement beyond the treated areas. In the Mekong Delta, approximately 83% of agricultural fields are smaller than 2 ha, with conventional and organic rice paddies often located side by side and typically separated only by low dykes, which offer minimal barriers to spray drift and the movement of agrochemicals (Tho and Umetsu, 2022). The dense network of rivers and artificial canals used for irrigation also connects fields regardless of management type, facilitating the transfer of pesticides from conventional to organic production (Biggs et al., 2009). This is also evident from the detection of DEET in sampled fields, despite it is not being sprayed on any conventional fields adjacent to the organic plot, indicating off-target pesticide movement. Additionally, various pesticides found at the sites, were detected not only in irrigation water but also in standing water on the fields themselves (Table 2). Because the water was largely stagnant rather than flowing, it remains unclear whether these contaminants originated primarily from the fields or via the irrigation system from neighboring paddies or production systems (upland cops or vegetables). Additionally, a resampling performed one year later in 2024 on the organically managed rice field also showed no significant difference ($p > 0.05$) in the total pesticide residue levels compared to the initial sampling in 2023. The presence of pesticide residues over time supports the hypothesis that cross-contamination, likely through shared irrigation water or spray drift, contributes continuously to pesticide intrusion into the organically managed fields. Collectively, these results indicate that the irrigation management, alongside spray drift and runoff, represents a major route for the intrusion and redistribution of pesticide residues across the paddy fields in the Mekong Delta.

Additionally, to the sampling in Vĩnh Long province in 2024 soil samples were taken from two rice fields located in An Giang and Đồng Tháp provinces, whereby only in Vĩnh Long a total of 10 ha are certified organic with neighboring conventionally managed rice fields. The field in An Giang is managed organically orientation according to the farmer's information but not certified yet, and the transition time is unknown. The fields at Đồng Tháp are managed under a low pesticide input regime due to its proximity to a national park, where pesticide use is restricted. Despite low or no pesticide inputs reported by the farmers, pesticide residues were still detected in the soil samples from all three fields. Although the Vĩnh Long site has been certified organic for six years, it nevertheless exhibited detectable pesticide residues, albeit with the lowest average sum of pesticide concentrations among the three fields. However, the presence of residues can be attributed to the long half-lives of certain pesticides, as well as potential cross-contamination via spray drift and shared water systems from surrounding conventional fields as already discussed. In An Giang, the average sum of pesticide concentrations were notably higher than those found in Vĩnh Long. This may be the result of the local environmental conditions, especially by the irrigation management, as during the flooding season low dykes allow floodwaters to flow across fields, eliminating a clear separation between organic and conventional paddies, therefore, facilitating pesticide contamination through floodwater. The highest average sum of pesticide concentrations was observed in Đồng Tháp province. This could be related to the regional management practices and environmental factors, despite restrictions on pesticide applications adjacent to the national park. Overall, the persistence of pesticide residues in these fields underscores the challenges in achieving residue-free conditions required for organic farming, particularly in landscapes with mixed land use, hydrological connectivity between conventional and organic production systems, and use of pesticides with long half-lives.

4. Conclusion

This study provides comprehensive data from farmer surveys on pesticide use in conventional rice production and residue analyses of

Table 2

Detected pesticide residues from the sampling sites in Vĩnh Long (VL-) province in 2023. Results are shown as mean concentrations (μg L^{-1}) in paddy water from the two conventional fields (VL-CA and VL-CB), one organic field (VL-O), and water of the irrigation channel connecting all three fields.

Vĩnh Long	Field Water		Field Water		Field Water	Irrigation Channel	
	VL-CA ($n = 2$)		VL- CB ($n = 6$)		VL-O ($n = 1$)	($n = 6$)	
	Mean	Max	Mean	Max	Max	Mean	Max
Insecticides							
DEET	0.071	0.079	0.096	0.128	0.098	0.129	0.365
Fenobucarb	0.002	0.002	0.003	0.006	0.001	0.005	0.013
Chlorantraniliprole	0.011	0.015	0.014	0.041	0.014	0.014	0.034
Imidacloprid	0.061	0.078	0.045	0.088	0.072	0.103	0.189
Thiamethoxam	n.d.	n.d.	0.002	0.005	n.d.	0.003	0.006
Dimethoate	n.d.	n.d.	0.001	0.001	n.d.	0.005	0.015
Fungicides							
Tricyclazole	0.480	0.515	0.217	0.357	0.300	0.224	0.432
Isoprothiolane	0.115	0.128	0.427	1.642	0.121	0.637	2.096
Tebuconazole	0.005	0.006	0.004	0.006	0.003	0.005	0.009
Metalaxyl	0.083	0.107	0.063	0.088	0.131	0.089	0.119
Propiconazole	0.213	0.373	0.184	0.390	0.020	0.161	0.431
Fluopyram	0.001	0.002	0.001	0.001	0.001	0.001	0.002
Difenoconazole	0.005	0.006	0.004	0.005	n.d.	0.006	0.009
Paclobutrazole	0.034	0.040	0.030	0.050	0.030	0.177	0.851
Hexaconazole	0.138	0.161	0.089	0.115	0.058	0.121	0.218
Fenoxanil	0.004	0.004	0.035	0.070	0.003	0.008	0.020
Azoxystrobin	0.022	0.028	0.021	0.027	0.019	0.040	0.090
Edifenphos	0.002	0.002	0.001	0.002	n.d.	0.001	0.002
Herbicides							
Pretilachlor	0.158	0.166	0.049	0.096	0.046	0.048	0.125
Flumetsulam	0.001	0.001	n.d.	n.d.	n.d.	0.001	0.001
2,4-D	0.064	0.074	0.212	0.435	0.086	0.185	0.468
Ametryn	0.003	0.004	0.002	0.003	0.003	0.002	0.004
Pyrazosulfuron-ethyl	n.d.	n.d.	0.004	0.004	n.d.	0.003	0.005
Quinclorac	0.291	0.291	0.927	1.119	0.188	0.709	1.329
Metalochlor	0.001	0.001	0.005	0.007	0.008	0.002	0.004
Atrazine	0.007	0.008	0.007	0.013	0.006	0.007	0.011
Niclosamide	0.012	0.012	0.006	0.011	0.007	0.007	0.012

soils and water from different management systems. Farmer surveys revealed the extensive use of diverse active ingredients in conventional rice production and also a suboptimal disposal of pesticide containers promoting pollution and cross-contamination around the agricultural fields. Analysis of the farmers' surveys did not only show an extensive use of diverse chemical substances but also the prevalence of insecticides targeting sap-sucking pests, particularly in An Giang province. This pattern underscores the ongoing challenges farmers face with these pests, as evidenced by continued struggles since the major planthopper outbreak in 2008. The persistent use of broad-spectrum insecticides poses a critical concern, as research demonstrates that these chemicals not only target pest species but also harm their natural enemies, such as predators of brown planthoppers, thus promoting pest outbreaks. This disruption of biological control mechanisms creates a cycle where pest problems are exacerbated rather than resolved, highlighting an urgent need for intervention.

The detection of pesticide residues in both conventional and organic farming soils at comparable concentrations, combined with the presence of unreported pesticides and contamination in irrigation water, indicates widespread cross-contamination between farming systems. This contamination is facilitated by Vietnam's agricultural landscape, characterized by small, fragmented farms typically spanning only a few hectares, shared irrigation infrastructure, and the absence of physical barriers such as high dykes between organic and conventional fields.

To address these interconnected challenges, this study recommends that farmers collaborate with each other and build farmer cooperatives to combine their fields into larger, more manageable units with proper physical separation between different farming systems. Additionally, implementing separate irrigation pathways would help minimize cross-contamination and preserve the integrity of organic farming practices while enabling more effective integrated pest management strategies. Such cooperative approaches represent essential steps towards sustainable rice production that balances pest control needs with environmental protection and supporting more sustainable biological agriculture.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used Perplexity for English language editing the manuscript to improve grammar and wording. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Linda Klamann: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Björn Thiele:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Giang Cao Dinh An:** Writing – review & editing, Investigation. **Nick Kupfer:** Writing – review & editing, Investigation. **Arne Kappenberg:** Writing – review & editing, Investigation. **Nguyen Thi Thu Nga:** Writing – review & editing, Investigation. **Tuan Quoc Vo:** Writing – review & editing, Investigation. **Khoi Chau Minh:** Writing – review & editing, Investigation. **Lutz Weihermüller:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2026.104773.

Data availability

Data will be made available on request.

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Glossary

AG: An Giang
ASE: Accelerated solvent extraction
DEET: N,N-diethyl-m-toluamide
DT: Đồng Tháp
EFSA: European Food Safety Authority
FAO: Food and Agriculture Organization of the United Nations
GSO: General Statistics Office of Vietnam
JAS: Japanese Agricultural Standards
LC-MS/MS: Liquid Chromatography-Tandem Mass Spectrometry
MeOH: Methanol
MONRE: Ministry of natural resources and environment Vietnam
SPE: Solid-phase extraction
VL: Vĩnh Long
VL-C: Vĩnh Long conventional managed field
VL-O: Vĩnh Long organically managed field
VL-CA: Vĩnh Long conventional managed field A
VL-CB Vĩnh Longconventional managed field B.:
VL- CC: Vĩnh Long conventional managed field C
WHO: World Health Organization