Pesticide Intensity in Rice Production in Central Thailand: Implications for Environmental and Health Risks

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***Abstract*—This study aims to assess the pesticide intensity in rice production in central Thailand by estimating the pesticide application rates, and the total mass loads of pesticide active ingredients, including screening pesticide contamination and effects on the surrounding environment and health risks. Data were collected using face-to-face in-depth interviews with farm owners, tenants and pesticide applicators from August 2021 to July 2022. The findings revealed a wide range of 50 pesticide active ingredients used in the rice production process in the central region, with five pesticides, namely, propanil, glyphosate, 2,4-D, difenoconazole and propiconazole, being the most frequently used for all rice varieties. Although Thailand has banned paraquat and chlorpyrifos, since 2020, they were still used in rice fields of RD rice (RD41 and RD61), Pathum Thani rice, and other rice varieties. Because of the largest planting area, the RD rice var. received the greatest pesticide mass load compared with other rice varieties. Using selected key parameters of pesticide physicochemical properties can help to screen environmental contamination and exposure risks for the pesticides used in the area.**

***Keywords*—environmental, health risks, pesticide, rice production**

I. Introduction

In Thailand, rice is an important economic crop for domestic consumption and export. Over the past decade, with an average of 9.7 million hectares of rice cultivation, Thailand has produced an average of 3.2 billion tonnes of rice yearly [1]. As for the world rice producer, Thailand ranked sixth after China, India, Indonesia, Bangladesh and Vietnam. In terms of the export industry, in 2021, Thailand was outstanding in exporting up to 6.4 million tonnes of milled rice and rice commodity products [2]. The achievement cemented Thailand's position as the world's second largest rice exporter after India, a testament to the country's dedication to the rice-growing industry. The central region of Thailand is the main rice-growing area. The production efficiency is about 3,800 kg per hectare (ha), which is the highest compared with other areas, namely, the North, East, West, Northeast and South [3].

To increase rice productivity, increased use of pesticides to protect crops from unwanted pests and weeds has become one of the significant factors in rice production. Based on the country's imported pesticide statistics estimates, total pesticide uses in the agricultural areas decreased from 3.53 in 2017 to 2.08 kg active ingredients (a.i.) per ha in 2020 [3]. However, these general application figures do not indicate an actual application rate for any particular crop or pesticide. Although a recent study conducted in Nakhon Sawan Province in central Thailand indicated that rice farming showed a high annual application frequency of herbicides glyphosate, paraquat and 2,4-D, and contributed the highest herbicide loads in the study area when compared with other cash crops (maize, cassava, and sugarcane), detailed records of insecticide and fungicide use remain unavailable [4].

Thailand grows many varieties of rice. According to the Department of Agriculture Extension, rice varieties are generally divided in five groups: Jasmine rice, Pathum Thani, RD Var., Provincial rice and others (Hom Nin, Red Jasmine, Sangyod and Riceberry) [5]. The number of pesticides used may vary depending on the rice varieties in each area. Any pesticide used can significantly impact both the surrounding environment (soil and water sources) and the health of agricultural workers and their families, as well as consumers [4, 6]. Medina *et al.* [7] reported that several pesticide residues were detected in polished and brown rice, husk rice and husk and bran. Such effects are due to the specific characteristics of pesticides used regarding their physicochemical properties related to their fate in the environment, including rice production and food processing. Therefore, identifying which pesticides are used and in what quantities in rice fields is crucial.

This study aims to comprehensively assess the intensive use of pesticides in rice production in Central Thailand by estimating the pesticide application rates and the total mass loads of all pesticide active ingredients found in different rice cultivars grown in the central region of Thailand. This thorough assessment will provide insight regarding pesticides a.i. and how much was applied in rice paddy fields, as well as screening for their contamination and effects concerning the surrounding environment and subsequent human health risks.

II. Materials and Methods

A. Study Area

Fig. 1 shows the boundary of the central region of Thailand, located between latitude 13°25' and 17°30'N and longitude 99°20' and 101°30'E, covering a total area of approximately 9.2 million ha (or 92,000 km^2). The main topography is a low land alluvial soil deposited by rivers, suitable for agriculture, especially rice cultivation. According to the Department of Agriculture Extension [5], the average total rice cultivation area over five years (2018 to 2022) was about 3.3 million ha (or 33,000 km^2), accounting for 36% of the total area of Central Thailand. The main rivers lie in the center of the region. The highest peak is about 1,500 m above mean sea level. Geographically, the area is divided in 22 provinces, as shown in Fig. 1 including Kamphaeng Phet, Nakhon Sawan,

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Suphan Buri, Lop Buri, Phetchabun, Uthai Thani, Saraburi, Chai Nat, Phichit, Phitsanulok, Nakhon Pathom, Ang Thong, Ayutthaya, Sing Buri, Pathum Thani, Nakhon Nayok, Nonthaburi, Sukothai, Samut Prakan, Samut Sonkram, Samut Sakhon and Bangkok [8]. The central region consists of four river basins: the Chao Phraya, Pasak, Tha Chin and Sakae Krang. The southwest and northeast monsoons influence the climate, with an average temperature of 27.5°C in 2021 and 2022. The average annual precipitation is approximately 1,759.3 to 2,012 mm [9].

In 2022, the total population of the central region was about 20 million, living in 9.8 million households. Approximately 13 % of all households were engaged in agriculture, with 61% growing rice [10].

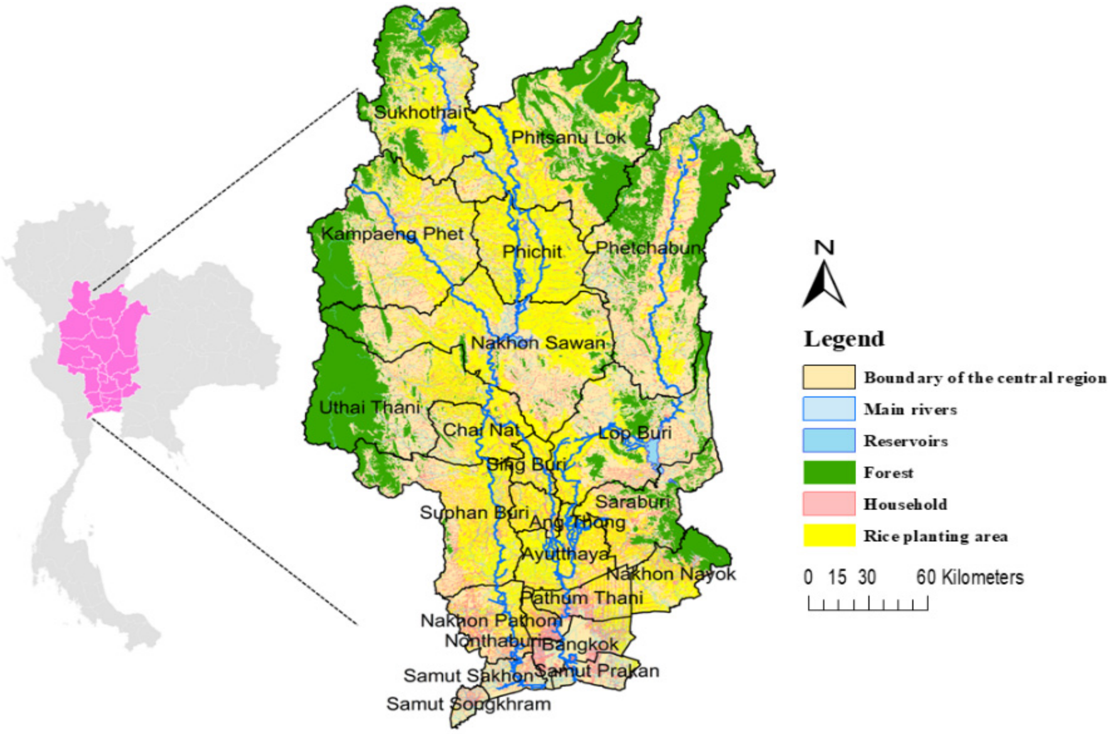

Fig. 1. Boundary of the central region of Thailand, showing 22 provinces and rice cultivation areas.

B. Data Collection

Data were collected using face-to-face in-depth interviews with rice farmers including farm owners, tenants, and pesticide applicators between August 2021 and July 2022. The interviews were conducted using random sampling in the study area. For interviews, we arranged an appointment through the village leader, district agricultural officer or local people to confirm whether the farmer, tenant or pesticide applicator would be available on the interview date. The data collected from the interviews covered various aspects such as farm size, type of rice grown, types and amounts of pesticide products used, frequency of application per crop and year and details of agricultural practices such as soil preparation, pre-emergence, postemergence, insect control, preharvest, and harvest, all of which are related to pesticides used.

Because one respondent may occupy more than one rice growing area, in different locations with different rice varieties and pesticide use, 117 datasets were collected from 83 interviewees. All datasets were divided and analyzed in five groups of rice varieties in this study: RD var. rice, Provincial rice, Pathum Tani rice, Jasmine rice and other minor rice varieties. The interview data were obtained from 15 provinces with large rice growing areas in the central region, namely Kamphaeng Phet, Suphan Buri, Lop Buri, Phetchabun, Uthai Thani, Chai Nat, Phichit, Phitsanulok, Nakhon Pathom, Ang Thong, Ayutthaya, Sing Buri, Pathum Thani, Sukhothai and Samut Prakan, covering an area of 2.6 million ha (or 26,000 km^2), accounting for 79% of the total rice growing area in the central region.

C. Pesticide Application Rate

The pesticide application rate is the amount of pesticide a.i. applied per hectare (ha) per year (yr). The amount of product applied, the area used and the percentage of a.i. in the pesticide products were obtained from in-depth interviews. The calculation formula can be expressed in Eq. (1) below.

$$m_{avg} = \frac{\Sigma\left[\frac{M_p}{a} \times M_{a.i.}\right]}{N} \quad (1)$$

where m_{avg} is the average pesticide a.i. application rate (kg a.i per ha per yr), M_p is amount of pesticide product applied for one interview dataset (kg), a is total area applied for one interview dataset (ha), $M_{a.i.}$ is percentage of a.i. in the pesticide product (%), and N is total interview datasets for rice cultivation.

D. Mass of Pesticide Applied to Rice Fields

The mass of pesticide applied to rice fields is the amount of pesticide a.i., that is applied to the rice-growing areas. The pesticide application rate is taken from Eq. (1). The cultivation areas of various rice varieties can be extracted from the statistics of the Department of Agriculture Extension [5]. The equation can be expressed in Eq. (2).

$$Mass_{pesticide} = m_{avg} \times Area^{rice} \quad (2)$$

where $Mass_{pesticide}$ is mass of pesticide applied to rice fields (kg per yr), m_{avg} is average pesticide a.i. application rate (kg per ha per yr), and $Area^{rice}$ is the rice-growing area (ha per year).

E. Criteria for Evaluating Environmental and Exposure Risks of Pesticide Use

To evaluate the pesticide fate in the environment and exposure risk, five key parameters of physicochemical properties representing various types of exposure likelihood: inhalation, surface water exposure, groundwater exposure, soil exposure and indirect ingestion from food were examined for individual pesticide use (adapted from [11–13]). The parameters included bio-accumulation, persistence in soil and water, water solubility, leaching potential to groundwater and volatility. Parameter data for environmental fate assessment was extracted from the Pesticide Properties Database (PPDB) developed by the Agriculture & Environment Research Unit (AERU) at the University of Hertfordshire: https://sitem.herts.ac.uk/aeru/ppdb [12]. The criteria for five parameters are summarized as shown in Table 1 (adapted from [12, 14]). The interpretation of the criteria is indicated by three colors: low or none (in yellow), moderate (in orange) and high (in red), according to the specified parameter values.

Table 1. Criteria for evaluating environmental fate and exposure risk of pesticide use according to pesticide physiochemical properties

Parameter	Value	Interpretation	Color
Volatility (mm Hg) at 20-25°C	< 5	Low	
	5–10	Moderate	
	> 10	High	
Solubility in water at 20°C (mg/L)	< 50	Low	
	50–500	Moderate	
	> 500	High	
Leaching potential (GUS* index)	< 1.80	Low	
	1.80–2.80	Moderate	
	> 2.80	High	
Bioaccumulation (log K_{ow})	< 2.70	Low	
	2.70–3.00	Moderate	
	> 3.00	High	
Persistence (day)	< 30	Non–persistent	
	30–100	Moderate persistent	
	100–>365 or stable	Persistent	

* Groundwater Ubiquity Score (GUS score) ranks the likelihood of a pesticide moving toward groundwater

III. Results and Discussion

A. Pesticide Use

Rice cultivation in the central region occurs twice yearly: major rice (in season) from August to November, and the second rice (off-season) from December to March. The most popular method of rice cultivation in this region is the pre-germinated direct-seeding system. The rice planting process involves several stages: soil preparation, pre-emergence, postemergence, insect control, pre-harvest and harvest. In this study, rice cultivars in the central region were divided in five groups: RD rice (RD41, RD61), Provincial rice (Phisanulok, and Suphanburi rice), Pathum Tani rice, Jasmine rice and other minor rice varieties (RD43, RD47, RD49, RD51, RD57, RD79, RD85, RD89 and Hom Nin). For the average five-year rice planting area of each variety group, RD rice had the largest area, accounting for 79.49%, followed by provincial rice, Pathum Tani rice, other rice varieties and Jasmine rice at 11.79, 6.39, 2.32 and 0.01%, respectively. Of the total 117 interview datasets gathered, 34% (*n*=40) were from RD rice var., followed by other minor rice varieties 22% (*n*=25), provincial rice var. 16% (*n*=19), Jasmine rice var. 15% (*n*=18), and Pathum Thani rice var. 13% (*n*=15). Table 2 summarizes all pesticide active ingredients (a.i.) used for rice production in the central region of Thailand. A wide range of 50 pesticide a.i. was found in different pesticide products used in the study area. This includes 22 herbicides, 18 insecticides and 10 fungicides a.i. In the central plain region, the top five most commonly used herbicides were propanil (52%), followed by glyphosate (48%), 2,4-D (45%), butachlor (37%) and clomazone (33%). As for insecticides, abamectin (35%) was the most frequently used, followed by chlorantraniliprole (28%), carbosulfan (20%), thiamethoxam (20%) and dinotefuran (20%). The most commonly used fungicides were difenoconazole (73%), followed by propiconazole (68%), azoxystrobin (23%) and tricyclazole (15%).

Table 2. List of pesticide active ingredients used in rice fields of the study area

Herbicide	%[1]	Insecticide	%[1]	Fungicide	%[1]
Propanil	52	Abamectin	35	Difenoconazole	73
Glyphosate	48	Chlorantraniliprole	28	Propiconazole	68
2,4-D	45	Carbosulfan	20	Azoxystrobin	23
Butachlor	37	Thiamethoxam	20	Tricyclazole	15
Clomazone	33	Dinotefuran	20	Propineb	3
Pretilachlor	31	Cypermethrin	18	Epoxiconazole	2
Glufosinate-ammonium	10	Chlorpyrifos	9	Fosetyl-aluminium	2
Pyribenzoxim	10	Emamectin benzoate	6	Isoprothiolane	2
Paraquat	7	Pymetrozine	5	Validamycin	2
Alachlor	5	Fipronil	4	Kasugamycin	1
Pendimethalin	5	Dichlorvos	4		
Pyrazosulfuron-ethyl	5	Cartap hydrochloride	3		
Ethoxysulfuron	4	Imidacloprid	3		
Bispyribac-sodium	4	Indoxacarb	3		
Fenoxprop-P-ethyl	3	Fenobucarb	2		
Thiobencarb	3	Carbaryl	2		
Cyhalofob-butyl	3	Lambda-cyhalothrin	2		
Profoxydim	3	Methomyl	1		
MCPA	3				
Penoxsulam	2				
Quizalofop-P-ethyl	1				
Triclopyr butoxyethyl ester	1				

[1] calculated from the frequency of each pesticide found in each rice field (dataset). Each farmer may occupy more than one rice field, and each farm uses multiple pesticide active ingredients.

B. Pesticide Application Rate

Fig. 2 displays the application rate of 50 pesticide a.i. in rice cultivation in the central region. The herbicides butachlor, alachlor, glyphosate and thiobencarb showed the highest application rates annually, at 1.88 kg a.i./ha/yr, 1.43 kg a.i./ha/yr, 1.16 kg a.i./ha/yr and 1.12 kg a.i./ha/yr, respectively. Among insecticides, fenobucarb showed the highest application rate at 3.13 kg a.i./ha/yr, followed by carbaryl at 2.63 kg a.i./ha/yr, dichlorvos at 1.86 kg a.i./ha/yr and cartap hydrochloride at 1.33 kg a.i./ha/yr. Propineb, fosetyl-aluminum and isoprothiolane showed the highest application rates among fungicides at 1.7 kg a.i./ha/yr, 1 kg a.i./ha/yr and 0.52 kg a.i./ha/yr, respectively.

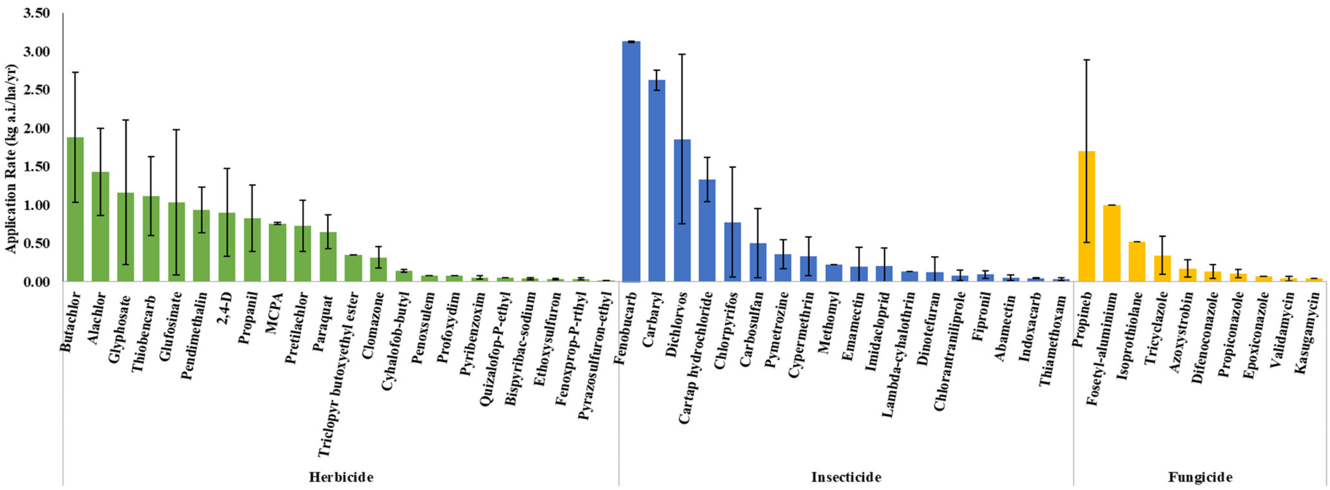

Fig. 2. Pesticide application rate in rice fields in the central region of Thailand.

Fig. 3 shows the average pesticide application rates for the different rice cultivars found in this study. With a total of 117 datasets, analyzing the use of pesticides was possible for five rice cultivar groups as classified in this study.

For the RD rice var. (Fig. 3a), a total of 31 types of pesticides were found to be used including 9 herbicides, 13 insecticides and 9 fungicides. The herbicides butachlor, glufosinate and glyphosate showed the highest application rates annually, at 1.95 kg a.i./ha/yr, 1.42 kg a.i./ha/yr and 1.02 kg a.i./ha/yr, respectively. Among insecticides, carbaryl had the highest application rate at 2.72 kg a.i./ha/yr, followed by cartab hydrochloride at 1.33 kg a.i./ha/yr and chlorpyrifos at 0.77 kg a.i./ha/yr. Propineb, fosetyl-aluminium, and Isoprothiolane had the highest application rates among fungicides, at 1.35 kg a.i./ha/yr, 1.00 kg a.i./ha/yr, and 0.52 kg a.i./ha/yr, respectively.

In the Provincial Rice var. (Fig. 3b), 12 types of pesticides were used. These included 8 herbicides, 1 insecticide and 3 fungicides. Alachlor, glyphosate and butachlor were the highest used herbicides with annual application rates of 1.87 kg a.i./ha/yr, 1.63 kg a.i./ha/yr and 1.49 kg a.i./ha/yr, respectively. Abamectin was the only insecticide used with an application rate of 0.04 kg a.i./ha/yr. Azoxystrobin, difenoconazole and propiconazole were the highest used fungicides with application rates of 0.13 kg a.i./ha/yr, 0.10 kg a.i./ha/yr and 0.08 kg a.i./ha/yr, respectively.

In the Pathum Thani rice var. (Fig. 3c), 17 types of pesticides were used including 10 herbicides, 3 insecticides and 4 fungicides. The herbicides butachlor, thiobencarb and 2,4-D had the high application rates annually, at 2.02 kg a.i./ha/yr, 1.88 kg a.i./ha/yr and 1.28 kg a.i./ha/yr, respectively. The insecticides carbosulfan, chloraniliprole and abamectin had the highest application rates annually, at 0.20 kg a.i./ha/yr, 0.14 kg a.i./ha/yr and 0.06 kg a.i./ha/yr, respectively. Fosetyl-aluminium, triclazole, and difenoconazole were the highest used fungicides with application rates of 1.00 kg a.i./ha/yr, 0.68 kg a.i./ha/yr and 0.11 kg a.i./ha/yr, respectively.

In Jasmine rice var. (Fig. 3c), 11 types of pesticides were used including 8 herbicides, 3 insecticides and 3 fungicides. The herbicides, glyphosate, 2,4-D and propanil had the highest application rates annually, at 1.25 kg a.i./ha/yr, 0.95 kg a.i./ha/yr and 0.85 kg a.i./ha/yr, respectively. Carbosulfan, thiamethoxam and dinotefuran were the most commonly used insecticides with an application rate of 0.49 kg a.i./ha/yr, 0.03 kg a.i./ha/yr and 0.03 kg a.i./ha/yr. Tricyclazole, difenoconazole and propiconazole were the most commonly used fungicides with application rates of 0.15 kg a.i./ha/yr, 0.12 kg a.i./ha/yr and 0.11 kg a.i./ha/yr.

Lastly, the other minor rice vars. used 35 pesticides including 15 herbicides, 14 insecticides and 6 fungicides (Fig. 3c). The herbicides, butachlor, glyphosate and alachlor had the highest application rates annually, at 1.73 kg a.i./ha/yr, 1.47 kg a.i./ha/yr and 1.11 kg a.i./ha/yr, respectively. Among insecticides, fenobucarb, dichlorvos, and carbosulfan had the highest application rates at 3.13 kg a.i./ha/yr, 2.01 kg a.i./ha/yr and 0.58 kg a.i./ha/yr respectively. Among fungicides, propanil, tricyclazole and azoxystrobin had the highest application rates at 3.03 kg a.i./ha/yr, 0.43 kg a.i./ha/yr and 0.23 kg a.i./ha/yr, respectively.

The study results revealed that five pesticides, namely, 2,4-D, glyphosate, propanil, difenoconazole and propiconazole, were used in all five rice variety groups. Pathum Thani rice had the highest application rate of 2,4-D at 1.28 kg a.i./ha/yr, while Provincial rice had the highest glyphosate application rate at 1.63 kg a.i./ha/yr. The highest propanil application rate was found at 1.01 kg a.i./ha/yr. in other minor rice varieties. For the two fungicides, difenoconazole and propiconazole, the highest use was found in RD rice at 0.15, and 0.12 kg a.i./ha/yr, respectively.

From the pesticide use results reported above, only 14 pesticides could be compared with the recommended pesticide use by the Department of Agriculture (DOA) of Thailand [15–18] (see Table 3). Of all the pesticides compared, nine exceeded the recommendation levels. This included glyphosate, alachlor, glufosinate, butachlor, abamectin, emamectin, difenoconazole, propiconazole and propineb. Although Thailand has banned the import, production and use of two pesticides, paraquat and chlorpyrifos, since June 2020 [19], these chemicals were still used in rice fields of RD rice, Pathum Thani rice and other rice varieties in the study area. The use of herbicides 2,4-D, propanil and insecticide cartap hydrochloride was found to be below recommended levels. However, the use of herbicide glufosinate exceeded the recommended level by 1.5 to 9.5 fold. Regarding insecticides, abamectin and emamectin were used on various rice varieties at levels exceeding the recommended level by 2 to 20 fold. All three fungicides (difenoconazole, propiconazole and propineb) were applied to all rice varieties at levels approximately 1 to 3 times higher than recommended levels.

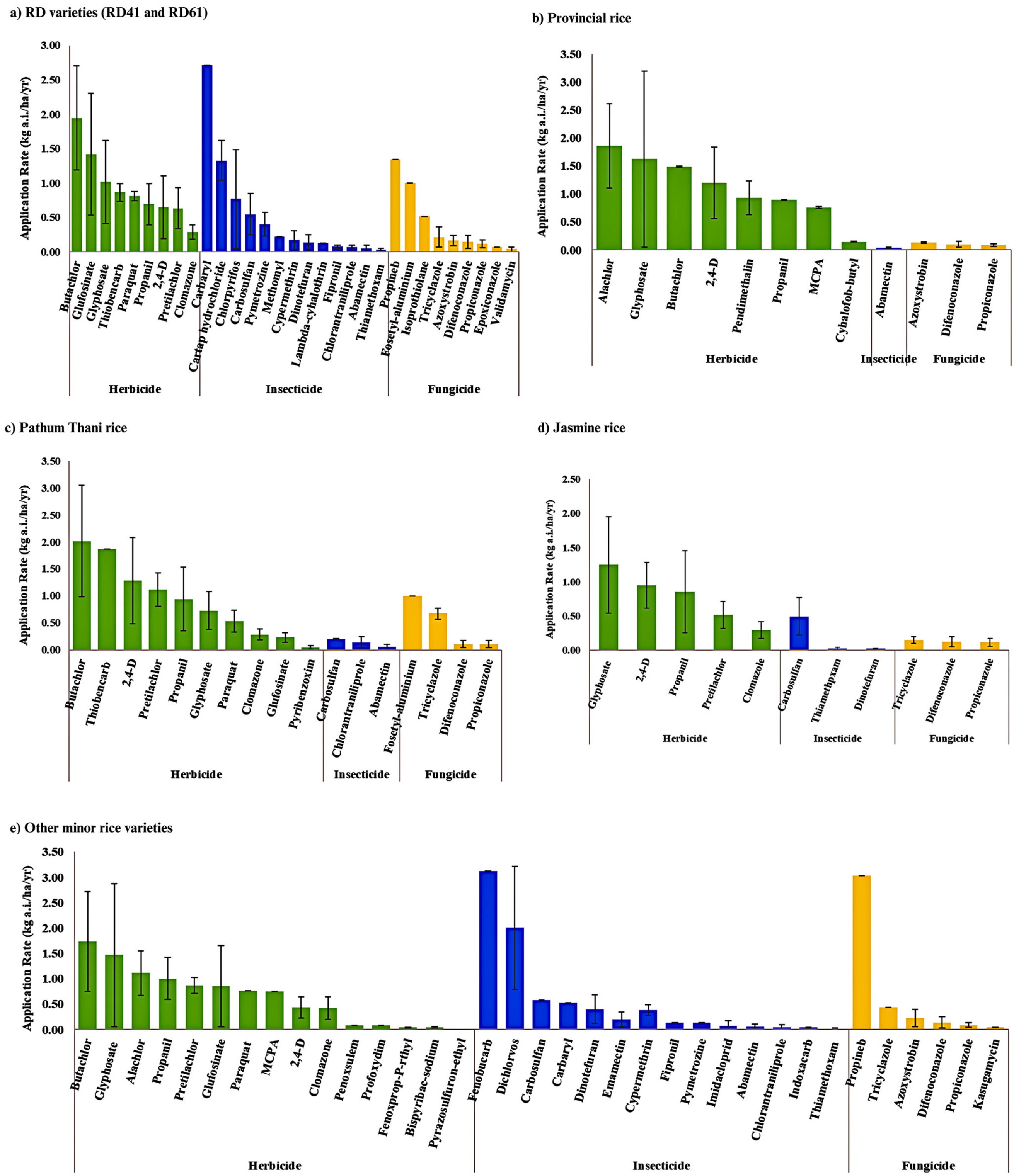

Fig. 3. Pesticide application rate in different rice variety groups: a) RD varieties (RD41 and RD61); b) Provincial rice; c) Pathum Thani rice; d) Jasmine rice; and e) other minor rice varieties.

Table 3. Comparison of pesticide application with recommendations

Pesticide	Application rate (kg a.i./ha/yr)						Recommendation (kg a.i./ha/yr)
	Overall	RD rice	Provincial rice	Pathum Thani rice	Jasmine rice	Others rice	
Herbicide							
Glyphosate	1.16 ± 0.95	1.02 ± 0.61	1.63 ± 1.57	0.73 ± 0.35	1.25 ± 0.71	1.47 ± 1.41	1.50 [1]
Alachlor	1.43 ± 0.57	-	1.87 ± 0.75	-	-	1.11 ± 0.43	1.68 – 1.86 [2]
Glufosinate	1.04 ± 0.95	1.42 ± 0.88	-	0.23 ± 0.09	-	0.86 ± 0.80	0.15 [2]
2,4-D	0.90 ± 0.57	0.65 ± 0.46	1.20 ± 0.64	1.28 ± 0.80	0.95 ± 0.34	0.44 ± 0.21	1.26 – 1.68 [1]
Butachlor	1.88 ± 0.85	1.95 ± 0.76	1.49 ± 0.01	2.02 ± 1.03	-	1.73 ± 0.98	0.90 – 1.20 [1]
Propanil	0.88 ± 0.43	0.69 ± 0.30	0.89 ± 0.01	0.95 ± 0.59	0.85 ± 0.60	1.01 ± 0.41	1.44 [1]
Paraquat	0.65 ± 0.22	0.81 ± 0.07	-	0.54 ± 0.20	-	0.77 ± 0.00	Banned [3]
Insecticide							
Abamectin	0.05 ± 0.04	0.05 ± 0.04	0.04 ± 0.01	0.06 ± 0.05	-	0.06 ± 0.05	0.02 [5]
Emamectin	0.20 ± 0.14	-	-	-	-	0.20 ± 0.14	0.01 [5]
Cartab hydrochloride	1.33 ± 0.29	1.33 ± 0.29	-	-	-	-	2 [4]
Chlorpyrifos	0.77 ± 0.72	0.77 ± 0.72	-	-	-	-	Banned [3]
Fungicide							
Difenoconazole	0.13 ± 0.09	0.15 ± 0.10	0.10 ± 0.05	0.11 ± 0.06	0.12 ± 0.07	0.14 ± 0.11	0.075 [4]
Propiconazole	0.11 ± 0.05	0.12 ± 0.06	0.08 ± 0.02	0.11 ± 0.06	0.11 ± 0.06	0.09 ± 0.05	0.075 [4]
Propineb	1.70 ± 1.19	1.35 ± 0.00	-	-	-	3.03 ± 0.00	1.05 [4]

[1] = Weed control recommendations in field crops 2022 [15]
[2] = Weed control recommendations 2011 [16]
[3] = Announcement of the Ministry of Industry regarding the list of dangerous substances (No. 6) B.E. 2563 (2020) [19]
[4] = Pesticide recommendation in safe protection and elimination of pests 2022 [17]
[5] = Pesticide recommendation in safe protection and elimination of pests 2023 [18]

C. Pesticide Mass Load

Based on the list of pesticide a.i. used in rice fields of the study area as shown in Table 2 above, the frequently used pesticides, more than or equal to 5% (≥5%) were selected to estimate the mass load of pesticides in this section. Table 4 shows the amount of pesticide loading for 25 types on rice fields in the central region of Thailand. The top five herbicide mass loads were butachlor, followed by glufosinate, glyphosate, 2,4-D and propanil, while insecticides were chlorpyrifos, followed by carbosulfan, pymetrozine, cypermethrin and dinotefuran.

In Table 4, five types of pesticides, namely glyphosate, propanil 2,4-D, difenoconazole and propiconazole, were used on all rice varieties, approximately 9,332 thousand kg per year. Of the total, glyphosate accounted for the largest share about 38%, followed by 2,4-D at 27%, propanil at 26%, difenoconazole at 5% and propiconazole at 5%. The mass loading analysis revealed that RD rice fields received the highest pesticide load, followed by Provincial rice, Pathum Thani rice, other rice varieties, and Jasmine rice.

Table 4. Mass of pesticide applied to rice fields in the central region of Thailand

Pesticide	Total mass load (1000 kg a.i. yr^{-1})					
	Total area (3,300,336 ha)	RD Var. (2,623,176 ha)	Provincial rice (390,327 ha)	Pathum Thani rice (209,550 ha)	Jasmine rice (240 ha)	Others (77,043 ha)
Herbicide						
Butachlor	6,247.79	5,109.69	581.64	423.28	-	133.18
Glufosinate	3,843.34	3,728.18	-	49.11	-	66.05
Glyphosate	3,571.63	2,669.18	635.54	153.54	0.30	113.07
2,4-D	2,481.56	1,708.87	470.26	268.63	0.23	33.57
Propanil	2,446.53	1,821.75	348.98	198.14	0.20	77.46
Paraquat	2,308.33	2,136.80	-	112.46	-	59.07
Pretilachlor	1,969.07	1,667.23	-	234.77	0.12	66.95
Clomazone	850.27	756.31	-	61.15	0.07	32.74
Alachlor	814.46	-	728.61	-	-	85.85
Pendimethalin	364.55	-	364.55	-	-	-
Pyribenzoxim	10.96	-	-	10.96	-	-
Pyrazosulfuron-ethyl	0.80	-	-	-	-	0.80
Insecticide						
Chlorpyrifos	2,019.85	2,019.85	-	-	-	-
Carbosulfan	1,529.14	1,441.79	-	42.78	0.12	44.45
Pymetrozine	1,067.26	1,056.56	-	-	-	10.70
Cypermethrin	480.39	450.89	-	-	-	29.50
Dinotefuran	381.92	350.77	-	-	0.01	31.14
Chlorantraniliprole	207.07	173.01	-	30.18	-	3.88
Abamectin	174.50	143.76	14.48	11.79	-	4.47
Thiamethoxam	84.21	82.45	-	-	0.01	1.75
Emamectin	15.41	-	-	-	-	15.41
Fungicide						
Tricyclazole	744.02	569.19	-	141.45	0.04	33.34
Azoxystrobin	493.22	424.88	50.78	-	-	17.56
Difenoconazole	461.84	387.53	40.15	23.59	0.03	10.54
Propiconazole	370.64	307.90	32.26	23.59	0.03	6.86

In light of this analysis; clearly, the higher the pesticide application level and the larger the rice cultivation areas, the greater the pesticide mass loaded in the rice field. Therefore, it could be concluded that the pesticide mass load is significantly influenced by two factors (see also Eq. (2)), that is, rice cultivation area and pesticide application rate, which also depends on the number of pesticide applications yearly.

D. Environmental and Exposure Risks of Pesticide Use

According to the study results shown in Table 2 (frequently used ≥5%), Table 3 (comparison with recommended levels), and Figs. 2 and 3 (high application rate) above, a total of 33 pesticides including 13 herbicides, 13 insecticides and 7 fungicides were selected to evaluate their potential environmental fate and exposure risks for rice production in the study area. Based on the PPDB data and criteria specified in Table 1, the evaluation results are presented in Table 5.

Regarding volatility properties, herbicide clomazone, insecticide fenobucarb and dichlorvos and fungicide isoprothiolane are considered the most hazardous chemicals due to their high vapor pressure (see Table 5, shown in red). These chemicals can be exposed to inhalation. When considering both water solubility and persistence in water, eight pesticides, including glyphosate, glufosinate, paraquat, clomazone, dinotefuran, thiamethoxam, fosetyl-aluminium, and tricyclazole, can potentially contaminate water and subsequently pose both on- and off-site exposure risks. Pendimethalin, difenoconazole and chlorpyrifos are all highly persistent in soil and bio-accumulated, affecting soil and the food chain through direct soil exposure and indirect ingestion from food.

Table 5. Potential environmental fate and exposure risk of pesticide use in rice cultivation

Pesticide	Volatility (mm Hg) at 20-25°C	Solubility in water at 20°C (mg/L)	Leaching potential (GUS* index)	Persistence (day)		Bio-accumulation (log K_{ow})
				Soil	Water	
Herbicide						
Butachlor	2.40×10^{-1}	20	1.23	56	n/a	4.5
Alachlor	2.90	240	0.8	14	0.5	3.09
Glyphosate	1.31×10^{-2}	100,000	0.21	16.11	Stable	-6.28
Thiobencarb	2.39	16.7	0.59	21	Stable	4.23
Glufosinate	3.10×10^{-2}	500,000	1.03	7.4	300	-4.01
Pendimethalin	3.34	0.33	-0.28	182.3	Stable	5.4
2,4-D	9.00×10^{-3}	243,000	3.82	4.4	7.7	-0.82
Propanil	1.93×10^{-2}	95	-0.51	0.4	Stable	2.29
Pretilachlor	1.33×10^{-1}	500	n/a	30	Stable	4.08
Paraquat	1.00×10^{-2}	620,000	-6.89	3,000	Stable	-4.500
Clomazone	27	1,212	2.72	22.6	Stable	2.58
Pyribenzoxim	9.90×10^{-1}	3.5	-1.46	n/a	26.9	3.04
Pyrazosulfuron-ethyl	1.47×10^{-2}	14.5	2.13	15	n/a	3.16
Insecticide						
Fenobucarb	48	420	1.23	18.5	20	2.78
Carbaryl	4.16×10^{-2}	9.1	2.02	16	12	2.36
Dichlorvos	2.10×10^{3}	18,000	0.69	2	4.7	1.9
Cartap hydrochloride	1.00×10^{-10}	200,000	n/a	3	n/a	-0.95
Chlorpyrifos	1.43	1.05	0.58	386	53.5	4.7
Carbosulfan	3.59×10^{-2}	0.11	0.89	21	0.5	7.42
Pymetrozine	4.20×10^{-3}	270	1.33	5	Stable	-0.19
Cypermethrin	6.78×10^{-3}	0.009	-1.99	22.1	Stable	5.55
Emamectin	3.00×10^{-8}	24	n/a	5	Stable	5
Dinotefuran	1.70×10^{-3}	39,830	4.85	82	Stable	-0.549
Chlorantraniliprole	6.3×10^{-9}	0.88	3.51	597	Stable	2.86
Abamectin	3.70×10^{-3}	0.02	n/a	25.3	Stable	4.4
Thiamethoxam	6.60×10^{-6}	4,100	3.58	50	Stable	-0.13
Fungicide						
Propineb	1.60×10^{-1}	10	n/a	4.3	1.5	-0.26
Fosetyl-aluminium	1.00×10^{-4}	111,300	-6.99	0.018	Stable	-2.1
Isoprothiolane	18.80	54	n/a	n/a	n/a	3.3
Tricyclazole	2.70×10^{-2}	596	3.89	450	Stable	1.4
Azoxystrobin	1.10×10^{-7}	6.7	3.1	78	8.7	2.5
Difenoconazole	3.33×10^{-5}	15	0.83	130	Stable	4.36
Propiconazole	5.60×10^{-2}	150	1.58	71.8	53.5	3.72

However, when considering the multimedia exposure pathway (more than one pathway), eight pesticides used for rice production in the region, namely, 2,4-D, clomazone, dinotefuran, thiamethoxam, paraquat, tricyclazole, chlorantraniliprole and difenoconazole, have the potential to contaminate the wider environmental compartments (in air, soil, surface water and groundwater) and subsequent exposure risks through multiple routes.

As mentioned above, for the five pesticides, namely, glyphosate, propanil 2,4-D, difenoconazole, and propiconazole, which were found to be the most frequently used pesticide in all types of rice fields, and contributed the highest mass load in rice fields, glyphosate, 2,4-D and difenoconazole, were considered potential environmental contamination and human health concern through surface water, surface water and groundwater, and soil and water, respectively. It can imply that because the largest RD rice area received a heavy pesticide mass load from the use of various pesticides, RD rice fields and the surrounding environment (soil, surface water and groundwater) were considered the highest cumulative risk areas, followed by the areas of Provincial rice, Pathum Thani rice, other minor rice varieties and Jasmine rice.

However, this study showed a kind of qualitative risk assessment that can help identify potential environmental contamination and risk exposure in terms of pathways and routes from the use of different pesticides in rice production found in this study. Overall, it becomes apparent that providing systematic application data for all used pesticides per crop as described in this study (list of all pesticides used, pesticide application rate, and mass load) is essential to provide insights for further quantitative assessment of human health impacts of pesticides in the future.

IV. Conclusion

In conclusion, this study found that in the central region of Thailand, a wide range of 50 pesticide active ingredients covering herbicides, insecticides and fungicides were used in different quantities in the rice cultivars produced. Glyphosate, 2,4-D, propanil, difenoconazole and propiconazole were the most commonly used pesticides in rice fields of the study area. The RD rice var. received the highest pesticide mass load compared with other rice varieties. The findings are clear that the intensive use of pesticides over rice fields can lead to large amount of pesticide loads entering the environment, resulting in widespread environmental contamination, and subsequent human health risk implications. Providing detailed information obtained on which pesticide active ingredients (a.i.) and in what quantities are applied in the rice production process is recommended and can be used to support the development of a baseline database on pesticide use for further planning to reduce the use of agricultural chemicals, to prioritize environmental risks, and to monitor associated health risks in the region.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

AW conducted the research, collected, and analyzed the data, and wrote the original paper; SK provided comments and suggestions, and edited the manuscript. All authors had approved the final version.

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