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AGRICULTURAL PESTICIDE USE IN THE UPPER CITARUM RIVER BASIN: BASIC DATA FOR MODEL-BASED RISK MANAGEMENT

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Abstract

Since the middle of the 20th century, pesticide use has been a primary foundation of global agricultural development. However, the massive usage of pesticides can have detrimental impacts on human health and the environment, particularly in the aquatic ecosystem. This study determined the use of pesticides in the agricultural area of the Upper Citarum River Basin (UCRB); a crucial water resource on Java Island. A survey of 174 farmers was conducted in eight districts along the basin by using the random walk and quota sampling method. The questionnaire was designed to acquire data about the amount and types of pesticides used by farmers. Pre-survey was conducted to evaluate the feasibility of the questionnaire draft. The respondents' answers were inputted into an equation to estimate the pesticide use per year. The survey results showed that 31 different pesticides were used for 21 types of crops. Profenofos and Mancozeb were the two most used pesticides, among all. The highest annual average used per hectare was reported for Chlorothalonil on tomato (32.2 kg/ha/year), followed by Mancozeb on corn (28.6 kg/ha/year), and Chlorpyrifos on chili (26.1 kg/ha/year). Overall, the pesticide use estimation in the study area is relatively high, with an annual average of 24.6 kg/ha/year. A comparison between prescribed and actual use on rice (representing more than 64% of the total surveyed area) showed that most pesticides are used in line with the prescriptions, but about a quarter is used in larger amounts than recommended. This comparison also revealed that some farmers use pesticides for rice that are not recommended for rice farming. In conclusion, the data presented in this study can be used to estimate pesticide emissions for environmental risk assessment and to support water quality monitoring, especially since public accessibility of pesticide information is commonly limited in Indonesia and other low- and middle-income countries.

Keywords: Crop; Data; Estimation; Farmer; Pesticide use; Questionnaire.

1. Introduction

Pesticides are used to protect and secure significant resources such as crops and human health against potential adverse impacts from pests, insects, weeds, and pathogens. As such, pesticide use has been a primary foundation of global agricultural development since the middle of the 20th century (Masiá et al., 2014; Silva et al., 2019). The number of worldwide pesticides used has been estimated at approximately 6 billion pounds in 2011 and 2012 (USEPA, 2017). This number keeps increasing, especially in developing countries (Akter et al., 2018; Balmer et al., 2019; Phillips McDouglas Agribusiness Intelligence, 2019). The extensive and inappropriate usage of pesticides can have adverse effects on crops, human health, and ecosystems, particularly in aquatic environments (Kapsi et al., 2019; Tsaboula et al., 2016; Verger & Boobis, 2013). To prevent those negative impacts, some countries strictly control and regulate pesticide use and marketing.

Convenient pesticide management depends on information about pesticide types and their used amounts. In 2008, Eurostat, the statistical office of the European Union, developed a collection of pesticide usage statistics for (1) arrangement of annual pesticide used estimation; (2) monitoring innovations over time (Coupe & Capel, 2016); (3) monitoring potential movement of pesticides into the water; (4) environmental protection; (5) consumer protection: providing information for residue monitoring; (6) operator protection (improving or optimizing use); (7) providing information for the consent of new pesticides; (8) policy advise during the review programs of existing pesticides. However, the public accessibility of pesticide use data is typically scarce, i.e., restrictive data issues, budgeting problems, poor registration, and the inadequacy of regulations from the authorities. Eurostat (2008) specifies that the cost benefits for collecting actual usage statistics exceed the investments. Pesticide Use Reporting Program in California in which farmers are obliged to report their pesticide use every month is a great example of pesticide data management (California Department of Pesticide Regulation (CDPR), 2000).

Pesticide use data can appear as sales and usage data. Unlike the usage data, sales data are more universal. It cannot be directly related to the actual use in time and space since they do not afford details on crop, application dose, season, and spatial variation (Eurostat, 2008). These details are required in order to estimate pesticide emissions, model surface water contamination, set risk priorities and identify mitigation measures (Al-Khazrajy & Boxall, 2016; Bidleman et al., 2002; Herrero-Hernández et al., 2017; Konstantinou et al., 2006; Van Gils et al., 2019). Usage data provide those kinds of details needed by the authorities, researcher, and water manager. Unfortunately, usage data is typically difficult to obtain or even unavailable for crops produced in an area, especially in low- and middle-income countries (Mariyono et al., 2018a). In Indonesia, detailed information on pesticide uses in agricultural activities, particularly vegetable and rice production, is still limited (Mariyono et al., 2018b). The use of pesticides in the Upper Citarum River Basin (UCRB) in West Java is high due to its massively farming practices, considering that this area is one of the crucial rice producers in Indonesia (Fulazzaky, 2010; Rochmanti, 2009).

Citarum River contamination due to pesticide use is a primary concern due to its role as a vital water resource on Java Island. A significant source of surface water pesticide contamination is through agricultural runoff (Bidleman et al., 2002; Konstantinou et al., 2006). For that reason, it is important to know the surface water concentrations of pesticides for estimating risks for ecology and human health (Al-Khazrajy & Boxall, 2016; Van Gils et al., 2019). Modeling the emissions, fate, and transport is one tool to obtain pesticide concentration in water. One essential variable in the emission estimation model is the pesticide use data, i.e., the amounts used and application frequency per crop type. However, this kind of data is not centrally available in Indonesia. This problem is considered as a missing link in the water monitoring system, especially for emission modeling. This study was initiated to fill that missing link.

This study intended to determine the pesticide use data by farmers in the UCRB and make it accessible for everyone to use, especially in model-based pesticide risk management. Furthermore, the data could be applied as a required input for the surface water emission model of pesticides in the Citarum River. A questionnaire survey of 174 farmers was performed to acquire the data. The survey was focusing on the types and amounts of pesticides used on major crop types in UCRB. The method proposed in this study was expected to be applied in other river basins to gather similar basic data.

2. Methods

2.1. Description of the surveyed area

The Upper Citarum River Basin (UCRB) is located between 107°15’36”- 107°57’00” E and 06°’43’48” - 07°’15’00” S (Figure 1). It is the upstream part of the Citarum River Catchment and drains into the Saguling Reservoir, west of Bandung City. The UCRB covers a total area of approximately 1,822 km^2, consisting of 93 districts in 6 regencies and two cities (Harlan et al., 2018; Statistics Indonesia, 2015). The agricultural area dominates the area where about 200,000 people work as farmers (Statistics Indonesia, 2015). According to a study by Rochmanti (2009), pesticide usage in the UCRB is high as a result of its massively farming practices, considering that this area is one of the crucial rice producers in Indonesia (Rochmanti, 2009;

Fulazzaky, 2010). Thereby, UCRB is a suitable location to apply a method of pesticide use data collection in this study.

The main agricultural crops grown in UCRB are vegetables and rice. Flowers and fruits are also grown but in small-scale fields. Table 1 presents an overview of the most common crop types in UCRB and their corresponding surface areas.

Table 1. Crop types, their surface area and percentage of total agricultural area in UCRB

Crops	Area (Ha)	Percentage (%)
Rice	41183	37.92
Corn	10377	9.55
Potato	6155	5.67
Cabbage	6091	5.61
Chili	4330	3.99
Cassava	3895	3.59
Coffee	1789	1.65
Tomato	1689	1.56
Sweet potato	1336	1.23
Spring onion	626	0.58
String beans	447	0.41
Carrot	439	0.40
Strawberry	84	0.08
Broccoli	38	0.04
Others	30125	27.74
Total	108604	100

Source: Statistics Indonesia (2015)

The average annual rainfall in the UCRB varies from 1200 mm to 3000 mm, with an average of 2215 mm. Almost 70% of this rainfall occurs in the wet season. The wet season typically starts in November and ends in April, with an average monthly rainfall of approximately 250 mm (typical range: 100-500 mm). During the dry season from June to September, monthly rainfall is usually less than 50 mm (Deltares, 2010). Other months constitute a transitional period. The high annual rainfall and the mean daily temperature that varies between 18˚C and 30˚C provide favorable climatic conditions for growing vegetables in the UCRB.

2.2. Survey design and data collection

A questionnaire was designed to obtain information about the amount and types of pesticides used by farmers living in the UCRB agricultural area. The questionnaire comprised 21 questions

(Supplementary data 1) that focused on: 1) general information about the respondents (name, gender, age, address); 2) farmland information such as area, type of crops, harvest, planting period, and planting frequency per year; 3) pesticide application data such as brands purchased, type of pesticide, quantity, and frequency of application.

A pre-survey was conducted among 20 farmers who were not included in the final survey to test the questionnaire. The pre-survey aimed to evaluate the feasibility of the questionnaire draft, the time needed for planning the survey, and whether the results were in line with the survey goals. Based on the results, the questionnaire draft was slightly edited, resulting in the final questionnaire.

For the final questionnaire, 174 farmers were surveyed in eight districts at different elevations along the UCRB (Figure 1), i.e., Lembang (n=26), Cihampelas (n=32), Solokan Jeruk (n=28), Ciparay (n=18), Majalaya (n=20), Pacet (n=7), Pangalengan (n=12), and Ciwidey (n=31). The survey was conducted between January and March 2016. For every location, we were accompanied by a local guide who was known in the local community and farmers were selected by walking the area and randomly selecting farms to visit.

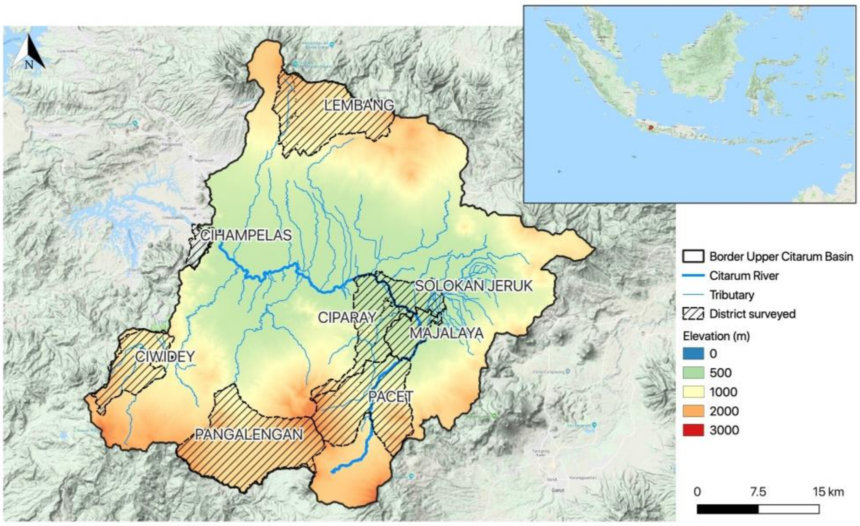

Figure 1. Location of the Upper Citarum River Basin (UCRB) in Indonesia (red dot in top right overview map). Districts (*Kecamatan*) in which the respondents were located, elevation and drainage system are shown in the main map. The respondents are stratified across elevation. Cihampelas, although just downstream of the UCB drains to the Citarum and represent respondents growing lowland crop types. The Pangalengan district extends across the mountain range; however, all respondents in this district are located inside the Citarum River Basin

The questionnaire survey was conducted by personal visits to the farmers in the daytime by two interviewers. The interview was face-to-face with voluntary participation, and each respondent was free to deny information without further justification. No farmer objected in practice, and all questionnaires included in the final dataset were complete for the pesticide use data. To protect the respondents' rights, dignity, safety, and well-being, ethical clearance was sought and issued by the Commission for Ethic of Health study from Dustira Hospital Cimahi, West Java. Each participant received a gift of staple food as compensation, such as instant noodles, coffee/tea, cooking oil, and sugar. The interviewers filled in the questionnaire forms. During the survey, interviewers recorded the respondent's answers and performed a crosschecking to confirm his or her response to avoid misunderstanding, especially regarding the pesticide application practice. For example, respondents were requested to show their equipments and materials of pesticide application to the interviewers. They also demonstrated their pesticide application habits to avoid misinterpretation. Interviewers checked the weight percentage or concentration of pesticide from each product, amount of application, and the brand package was also photographed for further reference. Whenever farmers used a container or spraying tank in their pesticide preparation, the container's or tank's dimensions or volume were measured.

2.3. Estimation of pesticide usage

Equation 1 was applied to estimate the pesticide use (i.e., expressed in active ingredient or a.i.) per year. Throughout the paper, the words pesticide and active ingredient are used as synonyms. We use the term "pesticide brand" to refer to a product of pesticides sold as a specific formulation.

$$Pa = \frac{C \times V \times f}{A} \tag{1}$$

Where, Pa is the annual amount of pesticide usage per hectare (g /ha/year), C is the concentration of the active ingredient in the product (g/l), V is the total spraying volume of pesticide brand (l/application), f is frequency of pesticide application (times/year), and A is the size of surveyed agricultural area of each individual farmer (ha). In case the applied pesticide was in solid form, its concentration was expressed as a weight percentage (Equation 2).

$$Pa = \frac{\%w \times W \times f}{A} \tag{2}$$

With the following new parameters, i.e., $\%w$ is weight percentage of a.i. in the pesticide brand (%) and W is the total weight of the pesticide brand used (g/application).

2.4. Comparing prescribed versus actual use

For rice, which covered almost 65% of the surveyed area, the prescribed use of pesticide was compared to the actual use. The data on the prescribed use was mostly taken from the Indonesian national guidelines (Directorate of fertilizers and pesticides, 2019). This was done per brand, since prescription instructions are brand specific. When information on the minimum and maximum prescribed use per hectare were available, these were compared with the actual use. When only prescribed dilution ranges were available, these values were also compared with the actual dilution value from the survey result. In case the brand was not recommended for use on rice, we used the minimum and maximum prescribed use values from other crops.

3. Results and Discussion

3.1. Results

3.1.1. Profile of the respondents and study area

The total number of respondents was 174, consisting of 30 female farmers (17.2%) and 144 male farmers (82.8%). The average age of surveyed farmers was 52 (± 11) years for female respondents, and 53 (± 12) for male respondents. From the 174 surveyed farmers, 156 (90%) used pesticides. The characteristics of the surveyed area and respondents are summarized in Table 2.

Table 2. Characteristics of the respondents and surveyed area

Information	Total	Percentage (%)	Average	SD
Gender				
Female	30	17.2	-	-
Male	144	82.8	-	-
Total respondents	174	100	-	-
Age				
Female	-	-	51.9	11.1
Male	-	-	53.3	12.5
Total respondents	-	-	53.1	12.3
Pesticide Use				
Nr. respondents using	156	89.7	-	-
Nr. respondents not using	18	10.3	-	-
Crops				
Average number of crops per farmer	-	-	1.4	-
Crop types	23	100	-	-
Area of pesticide use (m^2)				
Used	669196	90.3	-	-
Unused	72080	9.7	-	-
Size of surveyed area				
Area (m^2)	741276	100	-	-
Area per farmer (m^2)	-	-	4260.2	5285.7

The respondents manage 74.13 ha of an agricultural area in total, with an average value of 0.43 ha per respondent. Most farmers were full-time involved in agriculture. The respondents mentioned 23 crop types, of which rice was the most common crop (64.84%). Pesticides were applied on 90% of the surveyed area, no pesticides were used on banana and turmeric field. Table 3 summarizes the types, areas, and periods of the surveyed crops.

Table 3. Type, area, and planting period of crops in UCRB

Crop	Number of farmers planting	Total surveyed area (m2)	% Area	Planting period (months)		Frequency of planting per year (times/year)	
				Range	Average	Range	Average
Rice	111	480640	64.84	3 - 5	3.8	1 - 3	2.1
Chili	35	42677	5.76	3 - 6	3.9	1 - 4	2.7
Tomato	21	26763	3.61	3 - 4	3.2	1 - 4	2.3
Cabbage	19	29727	4.01	1 - 3.5	2.4	1 - 10	3.5
Coffee	8	81430	10.99	6 - 12	10.5	1 - 1	1.0
Broccoli	6	15960	2.15	2 - 3	2.3	2 - 5	2.5
Corn	5	9720	1.31	3 - 6	4.2	2 - 3	2.4
Spring onion	5	2940	0.40	2 - 3	2.2	4 - 6	5.4
Strawberry	5	4186	0.56	3 - 6	3.6	2 - 4	3.6
Carrot	4	3640	0.49	3 - 3	3.0	3 - 4	3.8
Potato	3	6300	0.85	3 - 3	3.0	3 - 4	3.3
String beans	3	2567	0.35	2 - 2	2.0	3 - 3	3.0
Cassava	3	6967	0.94	12 - 12	12.0	1 - 1	1.0
Sweet potato	3	3267	0.44	3 - 3	3.0	3 - 3	3.0
Chayote	2	8400	1.13	4 - 4	4.0	2 - 2	2.0
Lettuce	2	5600	0.76	1.5 - 3	2.3	2 - 2	2.0
Long bean	2	1447	0.20	3 - 3	3.0	3 - 3	3.0
Cauliflower	1	1167	0.16	-	2.5	-	2.0
Banana	1	1400	0.19	-	3.0	-	2.0
Eggplant	1	980	0.13	-	2.5	-	3.0
Turmeric	1	700	0.09	-	12.0	-	1.0
Bitter gourd	1	2800	0.38	-	2.0	-	5.0
Cucumber	1	2000	0.27	-	2.0	-	6.0
Total		741276	100				

3.1.2. Types of pesticides, pesticide – crop type combinations and frequency of application

The survey showed that 31 types of pesticides were used by 156 farmers. These pesticides consist of 18 insecticides, eight fungicides, two plant growth regulators (PGR), one rodenticide and two herbicides (Table 4).

Table 4. Pesticides used in UCRB, including CAS number, pesticide, and chemical group

Pesticide	CAS number	Pesticide group*)	Chemical group**)
2-Nitrophenol sodium salt	824-39-5	PGR	Sodium nitrocompound
4-Nitrophenol sodium salt	824-78-2	PGR	Sodium nitrocompound
Abamectin	71751-41-2	I	Avermectin
Alpha-cypermethrin	67375-30-8	I	Pyrethroids
Azoxystrobin	131860-33-8	F	Methoxy-acrylates
Beta-cyfluthrin	68359-37-5	I	Pyrethroids
Brodifacoum	56073-10-0	R	Hydrocoumarin
Carbofuran	1563-66-2	I	Carbamates
Chlorantraniliprole	500008-45-7	I	Diamides
Chlorfenapyr	122453-73-0	I	Pyrroles
Chlorothalonil	1897-45-6	F	Chloronitriles
Chlorpyrifos	2921-88-2	I	Organophosphates
Cypermethrin	52315-07-8	I	Pyrethroids
Deltamethrin	52918-63-5	I	Pyrethroids
Difenoconazole	119446-68-3	F	Triazoles
Dimehypo	52207-48-4	I	Nereistoxin analogues
Emamectin benzoate	155569-91-8	I	Avermectin
Endosulfan	115-29-7	I	Organochlorines
Imidacloprid	138261-41-3	I	Neonicotinoids
Lufenuron	103055-07-8	I	Benzoylureas
Mancozeb	8018-01-7	F	Dithio-carbamates
Maneb	12427-38-2	F	Dithio-carbamates
Mefenoxam (Metalaxyl-M)	70630-17-0	F	Acylalanines
Methomyl	16752-77-5	I	Carbamates
Metiram	9006-42-2	F	Dithio-carbamates
Metsulfuron-methyl	74223-64-6	H	Sulfonylurea
MIPC (Isoprocarb)	2631-40-5	I	Carbamates
Paraquat dichloride	1910-42-5	H	Bipyridylium
Profenofos	41198-08-7	I	Organophosphates
Propineb	12071-83-9	F	Dithio-carbamates
Spinetoram	187166-40-1	I	Spinosyns

*)PGR: Plant Growth Regulator; I: Insecticide; R: Rodenticide; F: Fungicide; H: Herbicide. **)Classification of the chemical group was based on MoA (Mode of Action) classification of Insecticide Resistance Action Committee (IRAC, 2019), Fungicide Resistance Action Committee (FRAC, 2019), Herbicide Resistance Action Committee (HRAC, 2010), and Rodenticide Resistance Action Committee (RRAC, 2015).

The raw results of the pesticide survey are listed in Supplementary data 2, consisting of concentration or weight percentage of the pesticide (based on information on the brand package), actual use, i.e., the application frequency and amount for each crop. Of the surveyed crops, the number of different pesticides used was highest in rice (15 types), chili and tomato (13 types for each), and cabbage (11 types). From the pesticides, Mancozeb and Profenofos were most often mentioned by the respondents with a total of 67 and 63 times, respectively. The pesticide – crop type combinations are summarized in Figure 2. The size of the squares indicates the number of fields that respondents report as a pesticide - crop type combination.

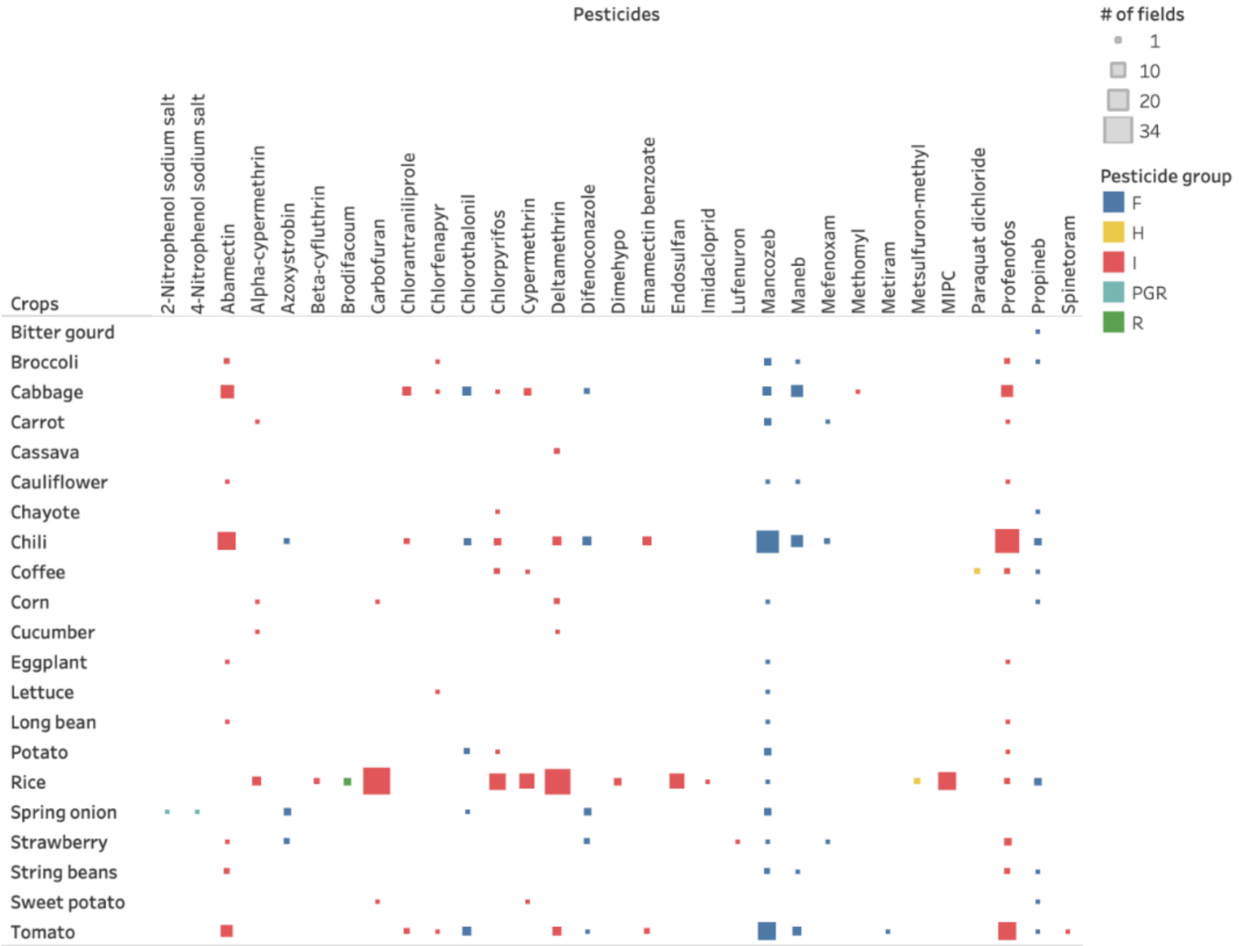

Figure 2. The number of agricultural fields per pesticide - crop type combination. The size of the squares corresponds to the number of fields on which the pesticide is applied, the color indicates pesticide group (PGR: Plant Growth Regulator; I: Insecticide; R: Rodenticide; F: Fungicide; H: Herbicide)

We found that Carbofuran and Deltamethrin were the two most frequently mentioned pesticides in rice farming, i.e., 34 rice fields were applied with Carbofuran and 32 rice fields with Deltamethrin. Carbofuran is used to control aphids, stem borers, and golden snails, and it is categorized as one of the most toxic Carbamate. While, Deltamethrin is used to control insect pests such as diamond back moth and cutworm (Fabro &Varca, 2012). The usage of rodenticides (Brodifacoum) and herbicides (Metsulfuron-methyl) in UCRB rice fields was low compared to the insecticides. Brodifacoum is typically used to control rats, while Metsulfuron-methyl is typically used to control weeds (Derbalah et al., 2019).

Profenofos and Mancozeb were widely used in vegetables cultivation, e.g. in chili and tomato fields (Figure 2). Twenty-six chili fields were treated with Profenofos, and 24 fields with

Mancozeb. For tomato, 15 fields were treated with Profenofos and 14 fields with Mancozeb. From the 13 types of pesticides which were used on tomato, 10 pesticides were also used on chili. It is because most tomato farmers also grow chili in this area. The result revealed that farmers generally used similar pesticides for different vegetable types; only the frequency and amount applied varied based on area and vegetable types.

To estimate the number of pesticides used, the concentration or weight percentage of each pesticide and its frequency of application are needed. These parameters vary per pesticide, crop type and farmer. The survey results show that farmers in the UCRB have developed their own dosage regimes, application frequencies and recipes for pesticide mixtures for their crops based on their experience. Almost all of them mixed multiple pesticides in the application, except for lettuce, chayote, cassava, and bitter gourd. The application frequency of each pesticide per crop type is depicted in Figure 3.

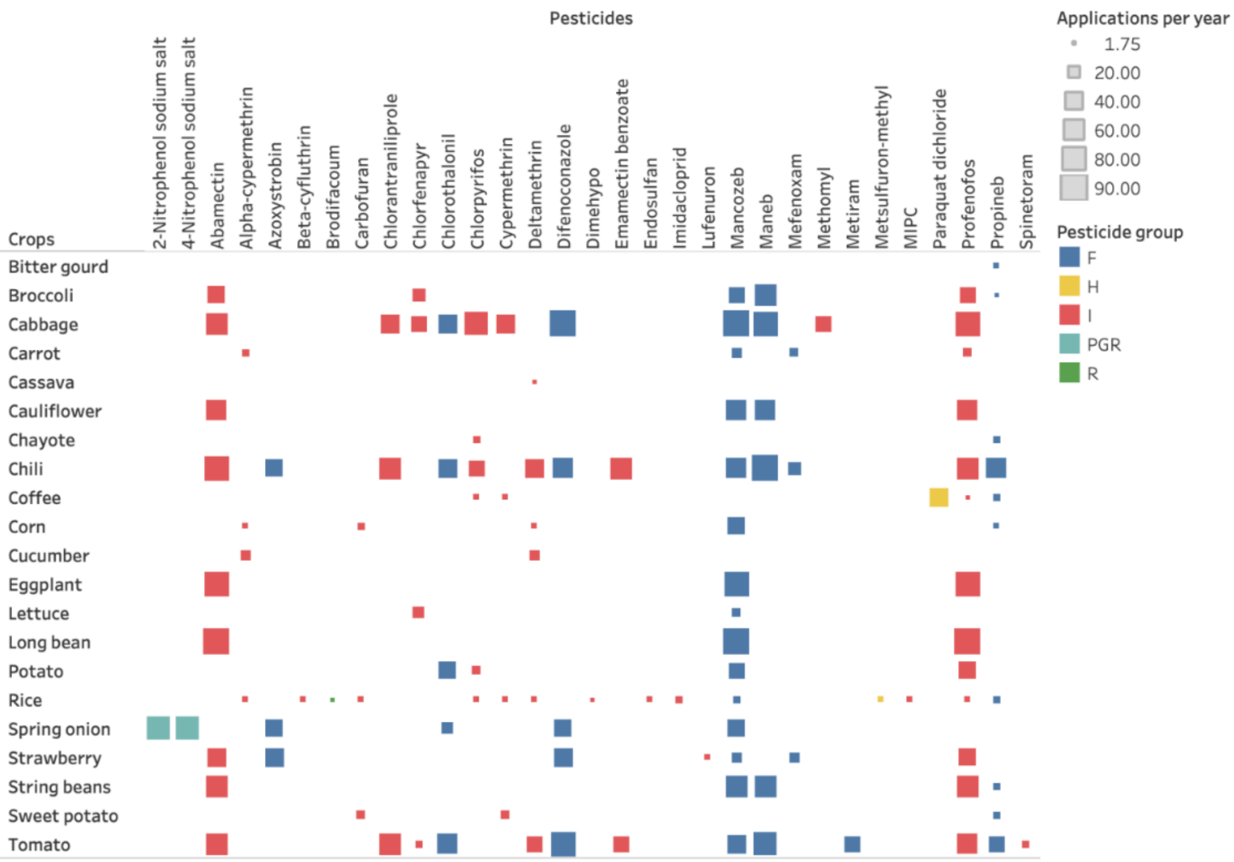

Figure 3. Number of pesticide applications per year. The size of the squares gives the number of applications per year, the color indicates group (PGR: Plant Growth Regulator; I: Insecticide; R: Rodenticide; F: Fungicide; H: Herbicide)
Source: Authors (2020)

The number of pesticide applications per year is based on the monthly average number of applications (this data is listed in Utami et al., 2020b). In case the farmer used more than one pesticide brand containing the same pesticide, this was counted as one application event. Figure 3 shows that the number of applications per year is highest on vegetables, most notably Abamectin, Mancozeb, and Profenofos in long bean, Difenoconazole and Mancozeb in cabbage, and Maneb in chili. In vegetables such as chili, tomato, and broccoli, Profenofos and Mancozeb were applied 5-7 times/month on average. Application frequency was even higher in cabbage with an average frequency of 8 - 10 times per month. These two pesticides are typically used to control mealy bugs, caterpillars, and whiteflies and handle leaf diseases because of leaf spots and rust (Derbalah et al., 2019). For rice, as the most surveyed crop, the application frequency is mostly less than once per month, or 1-3 times per growing season (3 - 4 months). Overall, Abamecetin, Mancozeb, Maneb, and Profenofos are pesticides that are applied at the highest frequency for most crops.

The pesticide-crop combination with the highest annual average amount of pesticide used per ha was Chlorothalonil on tomato with 32.2 kg/ha/year, followed by Mancozeb on corn with 28.6 kg/ha/year, and Chlorpyrifos on chili with 26.1 kg/ha/year. The pesticide-crop combination with the lowest average amount of pesticide used per ha per year was Brodifacoum on rice with $2 \cdot 10^{-4}$ kg/ha/year, then followed by Metsulfuron-methyl on rice and Cypermethrin on coffee with $7.2 \cdot 10^{-3}$ kg/ha/year and $1 \cdot 10^{-2}$ kg/ha/year, respectively.

3.1.3. The estimation of average annual use of pesticide per crop type

The estimation of annual average amounts of pesticide usage per hectare (g/ha/year) as calculated with Equation 1 and 2 are listed in Table 5.

Table 5. The annual average pesticide usage by the farmers in UCRB

Pesticide	CAS number	Average pesticide usage by farmers (g/ha/year)										
		Rice	Chili	Tomato	Cabbage	Coffee	Broccoli	Corn	Spring onion	Strawberry	Carrot	Potato
2-Nitrophenol sodium salt	824-39-5	-	-	-	-	-	-	-	77.1	-	-	-
4-Nitrophenol sodium salt	824-78-2	-	-	-	-	-	-	-	115.7	-	-	-
Abamectin	71751-41-2	-	460.3	311.7	189.7	-	112.6	-	-	280.5	-	-
Alpha-cypermethrin	67375-30-8	97.5	-	-	-	-	-	108	-	-	25.7	-
Azoxystrobin	131860-33-8	-	8057.1	-	-	-	-	-	9571.4	3051.4	-	-
Beta-cyfluthrin	68359-37-5	107.1	-	-	-	-	-	-	-	-	-	-
Brodifacoum	56073-10-0	0.2	-	-	-	-	-	-	-	-	-	-
Carbofuran	1563-66-2	1281.4	-	-	-	-	-	1714.3	-	-	-	-
Chlorantraniliprole	500008-45-7	-	2771.4	5371.4	1907.1	-	-	-	-	-	-	-
Chlorfenapyr	122453-73-0	-	-	771.4	642.9	-	7346.9	-	-	-	-	-
Chlorothalonil	1897-45-6	-	24857.1	32223.2	14169.6	-	-	-	14464.3	-	-	11571.4
Chlorpyrifos	2921-88-2	484.2	26150.3	-	1714.3	605.2	-	-	-	-	-	355.6
Cypermethrin	52315-07-8	155.7	-	-	11587.3	10.1	-	-	-	-	-	-
Deltamethrin	52918-63-5	95.6	130.7	92.1	-	-	-	180	-	-	-	-
Difenoconazole	119446-68-3	-	2875	428.6	232.1	-	-	-	5982.1	1907.1	-	-
Dimehypo	52207-48-4	2069.8	-	-	-	-	-	-	-	-	-	-
Emamectin benzoate	155569-91-8	-	1376.7	971.1	-	-	-	-	-	-	-	-
Endosulfan	115-29-7	776.2	-	-	-	-	-	-	-	-	-	-
Imidacloprid	138261-41-3	285.7	-	-	-	-	-	-	-	-	-	-
Lufenuron	103055-07-8	-	-	-	-	-	-	-	-	190.5	-	-
Mancozeb	8018-01-7	800	15181	16517.6	3635.3	-	16420.9	28571.4	25714.3	3085.7	7200	9536.5
Maneb	12427-38-2	-	15723	14978.8	4693.1	-	553	-	-	-	-	-
Mefenoxam (Metalaxyl-M)	70630-17-0	-	312.9	-	-	-	-	-	-	85.7	85.7	-
Methomyl	16752-77-5	-	-	-	4628.6	-	-	-	-	-	-	-
Metiram	9006-42-2	-	-	19200	-	-	-	-	-	-	-	-
Metsulfuron-methyl	74223-64-6	7.2	-	-	-	-	-	-	-	-	-	-
MIPC (Isoprocarb)	2631-40-5	1584.5	-	-	-	-	-	-	-	-	-	-
Paraquat dichloride	1910-42-5	-	-	-	-	4258.3	-	-	-	-	-	-
Profenofos	41198-08-7	1714.3	14411.5	10662.9	4301.5	108.7	7834.1	-	-	8099.6	3000	5142.9
Propineb	12071-83-9	3433.3	19022.2	12000	-	416.7	1250	3750	-	-	-	-
Spinetoram	187166-40-1	-	-	231.4	-	-	-	-	-	-	-	-

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Table 5. (continued)

Pesticide	CAS number	Average pesticide usage by farmers (g/ha/year)									
		String beans	Cassava	Sweet potato	Chayote	Lettuce	Long bean	Cauliflower	Eggplant	Bitter gourd	Cucumber
2-Nitrophenol sodium salt	824-39-5	-	-	-	-	-	-	-	-	-	-
4-Nitrophenol sodium salt	824-78-2	-	-	-	-	-	-	-	-	-	-
Abamectin	71751-41-2	141.9	-	-	-	-	66.9	199.3	55.7	-	-
Alpha-cypermethrin	67375-30-8	-	-	-	-	-	-	-	-	-	216
Azoxystrobin	131860-33-8	-	-	-	-	-	-	-	-	-	-
Beta-cyfluthrin	68359-37-5	-	-	-	-	-	-	-	-	-	-
Brodifacoum	56073-10-0	-	-	-	-	-	-	-	-	-	-
Carbofuran	1563-66-2	-	-	1285.7	-	-	-	-	-	-	-
Chlorantraniliprole	500008-45-7	-	-	-	-	-	-	-	-	-	-
Chlorfenapyr	122453-73-0	-	-	-	-	7346.9	-	-	-	-	-
Chlorothalonil	1897-45-6	-	-	-	-	-	-	-	-	-	-
Chlorpyrifos	2921-88-2	-	-	-	71.4	-	-	-	-	-	-
Cypermethrin	52315-07-8	-	-	487.9	-	-	-	-	-	-	-
Deltamethrin	52918-63-5	-	75	-	-	-	-	-	-	-	360
Difenoconazole	119446-68-3	-	-	-	-	-	-	-	-	-	-
Dimehypo	52207-48-4	-	-	-	-	-	-	-	-	-	-
Emamectin benzoate	155569-91-8	-	-	-	-	-	-	-	-	-	-
Endosulfan	115-29-7	-	-	-	-	-	-	-	-	-	-
Imidacloprid	138261-41-3	-	-	-	-	-	-	-	-	-	-
Lufenuron	103055-07-8	-	-	-	-	-	-	-	-	-	-
Mancozeb	8018-01-7	7406.2	-	-	-	4285.7	11020.4	6221.2	9183.7	-	-
Maneb	12427-38-2	829.5	-	-	-	-	-	691.2	-	-	-
Mefenoxam (Metalaxyl-M)	70630-17-0	-	-	-	-	-	-	-	-	-	-
Methomyl	16752-77-5	-	-	-	-	-	-	-	-	-	-
Metiram	9006-42-2	-	-	-	-	-	-	-	-	-	-
Metsulfuron-methyl	74223-64-6	-	-	-	-	-	-	-	-	-	-
MIPC (Isoprocarb)	2631-40-5	-	-	-	-	-	-	-	-	-	-
Paraquat dichloride	1910-42-5	-	-	-	-	-	-	-	-	-	-
Profenofos	41198-08-7	2261.4	-	-	-	-	3673.5	1728.1	3061.2	-	-
Propineb	12071-83-9	5000	-	3750	2000	-	-	-	-	1250	-
Spinetoram	187166-40-1	-	-	-	-	-	-	-	-	-	-

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3.1.4 Comparison of prescribed versus actual use

A comparison between prescribed and actual use was conducted to evaluate whether the pesticides were used according to the brand-specific prescriptions. The comparison was made for rice only, representing more than 64% of the total surveyed area in this study. Prescribed use was specified as the amount of pesticide brand per ha or sometimes as the amount of pesticide brand per L fluid per application. Table 6 summarizes prescribed and actual use data reported in the amount of pesticide brand per ha and Table 7 in the amount of pesticide brand per L fluid applied. Table 6 shows that 4 out of 15 brands (i.e., Curater 3 GR, Akodan 35 EC, Megathane 80 WP, and Allyplus 77 WP) had lower average values of actual use than the prescribed use range. Three out of 15 brands (i.e., Columbus 600 EC, Winder 100 EC, and Decis 25 EC) had higher average actual use values than the prescribed use range. Table 7 shows that the average actual use of 4 out of 10 brands (i.e., Dursban 200 EC, Rizotin 100 EC, Mipcinta 50 WP, and Curacron 500 EC) was lower than the prescribed use range, while only 1 brand (i.e., Winder 100 EC) had a higher value than prescribed. Comparison between prescribed and actual use in other crops are listed in Supplementary data 3.

Table 6. Comparison of prescribed and actual use of pesticide per hectare for rice. For pesticides without prescribed use for ricing the lowest and highest were taken from the other recommended crop types

Pesticide	Brand	Occur-rence	Prescribed use range		Actual use*)	Unit	Note
			Lowest	Highest	Average		
Alpha-cypermethrin	Fastac 15 EC	4	0.2025	1.5	**1.23**	l/ha	palm oil tree, soya bean, tea, chili
Beta-cyfluthrin	Buldok 25 EC	2	0.25	2	**1.70**	l/ha	chili, soya bean, tea, corn, cotton tree, pepper, tobacco, melon
Brodifacoum	Petrokum 0,005 BB	3	1	2	**1.92**	kg/ha	rice
Carbofuran	Curater 3 GR	3	12.75	17	**3.69**	kg/ha	rice
Carbofuran	Furadan 3 GR	32	8.5	25.5	**12.27**	kg/ha	rice
Chlorpyrifos	Columbus 600 EC	1	0.5	1	**2.38**	l/ha	shallot
Cypermethrin	Arrivo 30 EC	8	0.5	2	**0.90**	l/ha	corn, oil palm tree, tea, cotton tree
Cypermethrin	Columbus 600 EC	1	0.5	1	**2.38**	l/ha	shallot
Deltamethrin	Decis 25 EC	32	0.075	0.5	**0.78**	l/ha	palm oil tree, cucumber, melon, tobacco
Endosulfan	Akodan 35 EC	10	1.24	2.47	**0.75**	l/ha	all crops in general
Imidacloprid	Winder 100 EC	1	0.125	0.25	**0.95**	l/ha	rice
Mancozeb	Megathane 80 WP	1	2.625	2.625	**0.11**	kg/ha	potato
Metsulfuron-methyl	Allyplus 77 WP	2	0.32	1.5	**0.31**	kg/ha	rice
MIPC (Isoprocarb)	Mipcinta 50 WP	14	0.25	2	**0.82**	kg/ha	rice
Propineb	Antracol 70 WP	3	0.25	1	**0.76**	kg/ha	rice

*)Black color: the actual use is in the range of prescribed use, green color: the actual use is lower than the prescribed use, red color: the actual use is higher than the prescribed use

Table 7. Comparison of prescribed and actual dilution of pesticide per liter in rice. For pesticides without prescribed dilution for rice the lowest and highest were taken from the other recommended crop types

Pesticide	Brand	Occurrence	Prescribed use range		Actual use*)	Unit	Note
			Lowest	Highest	Average		
Alpha-cypermethrin	Fastac 15 EC	4	0.375	2	**1.69**	ml/l	cabbage, cacao tree, tobacco, tomato, watermelon
Beta-cyfluthrin	Buldok 25 EC	2	0.15	3	**1.41**	ml/l	orchid, grape, garlic, corn, orange, potato, coffee, apple, oil palm tree, shallot, soya bean, starfruit, chili, long bean, cacao tree, cabbage, manggo, melon, watermelon, tobacco, tomato
Chlorpyrifos	Dursban 200 EC	12	1.5	3	**1.06**	ml/l	chili, cacao tree, cabbage, tomato
Cypermethrin	Rizotin 100 EC	1	1.5	2	**0.63**	ml/l	cabbage
Cypermethrin	Arrivo 30 EC	8	0.5	4	**2.25**	ml/l	shallot, chili, orange, soya bean, potato, cucumber, melon, tomato, cashew tree, cacao tree, pepper, watermelon, tobacco
Deltamethrin	Decis 25 EC	32	0.25	2	**1.71**	ml/l	orchid, Jatropha curcas, orange, long bean, coffee, apple, starfruit, shallot, chili, corn, green bean, watermelon, cacao tree, soya bean, tea, potato, cabbage, mango, melon
Imidacloprid	Winder 100 EC	1	1	1	**1.96**	ml/l	rice
MIPC (Isoprocarb)	Mipcinta 50 WP	12	3	3	**1.61**	g/l	rice
Profenofos	Curacron 500 EC	2	1.125	2.25	**0.75**	ml/l	shallot, chili
Propineb	Antracol 70 WP	3	0.7	6	**0.78**	g/l	grape, cabbage, apple, Jatropha curcas, cucumber, krisan flower, mango, palm oil tree, shallot, orange, petsai, tobacco, garlic, chili, clove, strawberry, peanut, potato, kina, coffee, pepper

*)Black color: the actual use is in the range of prescribed use, green color: the actual use is lower than the prescribed use, red color: the actual use is higher than the prescribed use

3.2. Discussions

3.2.1. Pesticide use

We interviewed 174 farmers to obtain an impression of pesticide use on the farmed crops. The majority (154 farmers) were using pesticides, and the most frequently used pesticide groups were insecticides and fungicides. Most of the pesticides that we found in our survey were introduced on the market in the 20th century, with the insecticides Chlorantraniliprole (2008) and Spinetoram (2007) as notable exceptions. Thirteen of the 31 pesticides (i.e. Mancozeb, Profenofos, Chlorothalonil, Cypermethrin, Carbofuran, Beta-cyfluthrin, Propineb, Abamectin, Mefenoxam, Maneb, Dimehypo, Emamectin, Deltamethrin) that we identified were also reported by Sekiyama et al. (2007) who performed a study on the use of pesticides in the Citarum River Basin in 2006. The widest used pesticides in our survey were Profenofos (in 13 of 21 crop types) and Mancozeb (in 15 of 21 crop types) which is in line with the results of Sekiyama et al. (2007) who reported 13.5% and 24.3% of their respondents using these two pesticides, respectively. Of the 10 most frequently used pesticides reported by Sekiyama et al. (2007), we did not find Permethrin (insecticide), Spinosad (insecticide), Iprodione (fungicide), Dimethomorph (fungicide) and *Bacillus thuringiensis* (biological). This illustrates the dynamic nature of pesticide use which is governed by a variety of factors such as supply by industry, authorization by the government and farmer-specific considerations (Mariyono et al., 2018a).

The average pesticide usage was influenced by the frequency of application on each crop type. The frequency of pesticide application on vegetables was highest (7-10 times/ month) while for rice the lowest (1-3 times/growing season). The annual average of pesticide usage in UCRB range from $2 \cdot 10^{-4}$ kg/ha (Brodifacoum on rice) to 32.2 kg/ha (Chlorothalonil on tomato). On average, 24.6 kg/ha pesticide is applied annually on UCRB agricultural land, which is lower than Bahamas and Mauritius with 59.4 kg/ha and 25.5 kg/ha, respectively (Ly, 2013). But it is relatively higher compare to other Asian countries, such as 14 kg/ha in China (Yang et al., 2014), 7.2 kg/ha in Malaysia, 13.1 kg/ha in Japan, and 0.2 kg/ha in India (Ly, 2013). This high estimation is plausible because our study area represents a densely populated and intensively farmed landscape.

Maggi et al. (2019) estimated crop-specific pesticide use (kg/ha) globally. When comparing overlapping crop types and pesticides used in Maggi et al. (2019) and our study, we notice a mismatch: for rice and corn all applied pesticides differ; for cabbage we share one common pesticide (Chlorothalonil); Chlorpyrifos and Azoxystrobin are also present in Maggi et al. (2019) but for different crops. We conclude that pesticide use is very region specific and are not sure a global map of pesticide use distribution is representative for actual use.

Our results on prescribed versus actual use on rice show that farmers use pesticides for rice that are not recommended for rice farming. Most types of pesticides are used (per hectare or as diluted with water) more than the lowest recommended amounts; about a quarter are used more than the highest recommended amount. For rice farmers in Sulawesi, Indonesia, Batoa et al. (2019) found that the prescribed frequency (influencing use-per-hectare) and dose were followed by about 1/3 of the interviewed farmers, while 2/3 deviated from recommended frequency and dose in both higher and lower than recommended. Zhang et al. (2015) reported under- and overuse for Chinese farmers for various crops. Mariyono et al. (2018) reported overuse on Java Island, Indonesia, but they did not specify the pesticide type. A study by Fan et al. (2015) in China showed that most of the surveyed farmers lacked competence in understanding the guidance manuals or pesticide instructions. Additionally, the farmers often failed in selecting a suitable pesticide to resolve a specific pest or weed problem (Akter et al., 2018). These kinds of problems are also common in other agricultural areas (Akter et al., 2018; Fan et al., 2015; Houbraken et al., 2016). It stresses the importance of having transparent national pesticide usage guidelines and training farmers thoroughly in pest management, i.e. the diagnosis as well as the application of pesticides and alternative pest control strategies.

The survey showed that some rice farmers still used Endosulfan, usually to control stem borers, and green and brown leafhoppers (Derbalah et al., 2019; Fabro & Varca, 2012). Endosulfan is an organochlorine compound that was internationally banned in 2011 via the Stockholm Convention (Balmer et al., 2019; UNEP, 2011). Another banned insecticide found in the survey was Chlorpyrifos. The use of Chlorpyrifos in Indonesia is banned in rice agriculture (Ministry of Agriculture Republic of Indonesia, 2011; Ministry of Agriculture Republic of Indonesia, 2015). Sousa et al. (2018) found that concentrations of Chlorpyrifos and Endosulfan in most developing Asian countries, e.g. India, exceeded the values of the European Environmental Quality Standards (EQS) suggesting potential harm for aquatic ecosystem. Therefore, it is very important to monitor and enforce the usage guidelines, especially for these two pesticides.

3.2.2. Gathering usage statistics

The availability of pesticide use data is publicly scarce, i.e. due to restrictive data issues, poor registration, and inadequacy of regulations from the authorities. Sales statistics combined with the recommended use of national institutions offer some insight into the types and amounts of pesticides used, but such data are generally only available at higher spatial scales (Galimberti et al., 2020). More detailed pesticide use statistics are needed for local environmental risk assessments, monitoring the potential movement of pesticides into the water by using a model, operator protection (improving or optimizing use) and consumer protection (guiding residue monitoring) (Eurostat, 2008). It should be stressed that pesticide use data could be a valuable input to an emission model that is important for decision support in environmental risk management (Galimberti et al., 2020).

Although pesticides are among the most toxic substances released into the environment, very little public information is available on their use patterns, especially at the level of brands, active ingredients and at refined spatial scales. Our pesticide data results show that farmers do not always apply the pesticides to the prescribed crop types. The amounts applied vary, sometimes exceeding the highest recommended dose. In some cases, brands containing the same pesticide are applied simultaneously. Finally, the frequency of application also varies per farmer.

Information on which pesticide is used where and when, and in what quantities, is essential for protection of human health and the environment, as well as for effective pest management. In our opinion, a data should be public because people have a right to know all information about what, where, and how pesticides are being applied in order to take a suitable and effective measures to protect themselves and also the environment. Accurate information on pesticide use enables better risk assessments and supports the identification of problematic use practices so they may be targeted for developing alternatives (PAN Germany, 2003). Comparison of our results with a previous study on pesticide use in the UCRB (Sekiyama et al., 2007) shows considerable differences in pesticide use over time between these studies, indicating that results of single surveys are representative for a limited timeframe only. Gathering representative data over a longer timeframe requires the establishment of a pesticide use reporting system. California's pesticide-use reporting system produces the largest undertaking of this kind, and may represent as an example of future disclosure program of the pesticides usage data (CDPR, 2000).

3.2.3. Reducing pesticide use

Our results may be used to identify management options for reducing pesticide use. For example, the results show that crops like tomatoes, chili and cabbage require more pesticides than rice, cauliflower, and eggplant. Also, Mariyono et al. (2018a) reported that pesticide use even differs between local varieties and cultivated varieties within a crop type, where local varieties need more pesticides. Managers may consider stimulating the production of crops, or crop varieties, that demand less pesticides. Another option is to replace more toxic pesticides with less toxic alternatives. However, most of the pesticides used in the UCRB fall in WHO class 5 ("may be harmful if swallowed"), with only a few pesticides falling in categories 2 or 3 ("fatal/toxic if swallowed"; IPCS, 2010).

A more refined identification of management interventions would be possible if we would understand why farmers choose various pesticides, why they use the dosages and application frequencies as they do and sometimes overrule the prescriptions. In Sulawesi, Indonesia, Batoa et al. (2019) found that 73% of rice farmers interviewed state to know the use rules, whereas about 27% know little or nothing about prescribed use. So, the majority seem to know the recommendations and knowingly deviate. However, in contrast, Zhang et al. (2015) reported both under- and overuse for Chinese farmers and said it may be related to lack of knowledge. Bagheri et al. (2019) studied the drivers of farmers' intentions to use pesticides. Including an assessment of knowledge and motivations of use could improve understanding and estimations of pesticide use especially when extrapolating survey data. With insights in farmers' motivations, the extrapolation of the data to other regions can be more precise or can be applied in intervention scenarios to estimate the effects of social- or financial interventions.

4. Conclusion

The survey found that 90% of the farmers in UCRB use pesticides on their fields. In total, 31 pesticide types were found in the survey area with Mancozeb and Profenofos as two most commonly used pesticides by the farmers, especially in chili and tomato fields. In terms of application frequency, highest frequencies were recorded for Abamectin, Mancozeb, and Profenofos in long bean, Difenoconazole and Mancozeb in cabbage, and Maneb in chili. These variations in pesticide application frequency influenced the yearly amount of the pesticides applied for each crop in the UCRB. The highest annual average amount of pesticide used per ha of pesticide-crop combination was Chlorothalonil on tomato, followed by Mancozeb on corn, and Chlorpyrifos on chili. Overall, the pesticide use estimation is relatively high with annual average of 24.6 kg/ha/year. Comparing prescribed and actual use on rice showed that most pesticides are used (per hectare or as diluted with water) more than the lowest recommended amount, and about a quarter is used more than the highest recommended amount. This comparison also indicated that some farmers use pesticides for rice that are not recommended for rice farming. Two banned pesticide (Endosulfan and Chlorpyrifos) were still used in the study area. It is very important to monitor and enforce the usage guidelines, especially for these two pesticides.

The presented data in this study is essential for further study such as predicting pesticide concentration in the surface water and estimating risks for ecology and human health. This study is considered to fill a missing link in the water monitoring system, especially for emission modeling because data on pesticide use in Indonesia and other low- and middle-income countries are scarce. The basic data in this study have been used to estimate pesticide use for environmental risk assessment. With these data, a first scoping can be done on the potential impact of regional pesticide use, such as establishing a water quality monitoring program targeting specific chemicals for analysis. Furthermore, advanced research on pesticide use motivations (types, under-or overuse) is recommended to improve estimates and facilitate sustainable pest management. It is also necessary to record pesticide usage on a regional and national level periodically to assess associations more precisely between chemicals usage and human health or ecosystem disruption.

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Author Contribution

Rosetyati R. Utami conceived of the presented idea. Rosetyati R. Utami and Getjan W. Geerling developed the theory and performed the computations. Indah R. S. Salami and Ad M.J. Ragas verified the analytical methods. Indah R. S. Salami, Suprihanto Notodarmojo and Ad M.J. Ragas supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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