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RESEARCH ARTICLE **OPEN ACCESS**

Comparison of Carbon Footprint, Environment Impact, Efficacy and Benefit–Cost Ratio of Insecticide Resistance Management with Conventional Methods used by Thai Chinese Cabbage Farmers

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Abstract:

Aim: To evaluate and compare the carbon footprint, efficacy, and benefit-cost ratios of Chinese cabbage grown via insecticide resistance management with two farming methods used by Thai farmers.

Background: Insecticide usage is currently being reduced by the employment of sustainable products and the promotion of environmentally friendly methods, thereby increasing the income of Chinese cabbage farmers in Thailand.

Methods: This study aims to evaluate the control of insect pests and marketable produce in Chinese cabbage using various methods. Pests were counted every five days, and the marketable produce was evaluated. Greenhouse gas emissions and environmental impact were estimated using methodologies such as the environmental impact quotient, with the pesticide usage costs and benefit-cost ratios recorded.

Results: The study compared two farming methods with insecticide resistance management, revealing that in the growing of Chinese cabbage, the latter exhibited lower emissions per acre and kg. However, the environmental impact was higher in methods 1 and 2 due to the increased spray application involved. The insecticide resistance management method was found to effectively control pests and produce marketable produce with less total investment and labour expenses.

Conclusion: The study analysed the impact of farming practices and pesticide resistance management strategies on the environment and carbon emissions. The results showed that insecticide resistance management is more effective in reducing carbon emissions and positively impacting the environment while also providing a better benefit-cost ratio. However, the study suggests that education and continuous monitoring are required for effective resistance management. The findings also emphasise the need for adaptation to changing pests and the consideration of external factors such as market demand, climate change, and government policies to ensure long-term sustainability.

Keywords: Carbon footprint, Greenhouse gas emission, Chinese cabbage, Benefit-cost ratio, Insecticide resistance management, Insecticide rotation.

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1. INTRODUCTION

One main cause of climate change is agriculture [1, 2]. In total, 17% of all greenhouse gas emissions are currently produced by agriculture [1-4]. Despite having a large agricultural sector, Thailand's greenhouse gas emissions (51.88 $TgCO_2eq$, 22.6%) are surpassed only by the energy sector (159.39 $TgCO_2eq$, 69.6%) [5]. Cultivation techniques and procedures used in agricultural production and product utilisation affect emissions. Farmers grow Chinese cabbage year-round in every part of Thailand to suit domestic demand. Chinese cabbage is an economically significant vegetable in Thailand. The cultivated area in 2020 was roughly 27,600 acres, with an average yield of 12,750 kg/acre. Overall, 45,162 tons have been produced [6]. The plant's extreme susceptibility to several insect pests, such as the leaf-eating beetle (*Phyllotreta sinuata*), cabbage webworm (*Hellula undalis*), and diamondback moth (*Plutella xylostella*), is one main issue influencing its production [7]. Farmers often spray many chemical pesticides during the growing season to tackle this issue [8-10]. However, overuse of pesticides leads to problems with insect resistance, control effectiveness and environmental issues. Methods to manage and achieve a low carbon footprint by lowering greenhouse gas emissions must be examined to decrease the above issues.

The Pesticide Resistance Action Committee divides insecticides into 36 groups according to their modes of action and emphasises the necessity of rotating different pesticide groups to discourage resistance. It is linked to one traditional approach to controlling insect pests [11]. To combat pest infestations in Chinese cabbage effectively, precise and accurate data on insecticide application are necessary. This strategy aligns with the insecticide resistance management goals of reducing pesticide residues in agricultural goods and postponing the emergence of insecticide resistance. The strategy involves effective insecticides from different groups with different modes of action suited to different stages of pest life or periods. Importantly, these insecticides cannot show cross-resistance to previously used chemicals for rotation schemes to work [12]. Applying this strategy properly, benefits the economy and meets consumer demands for safe and high-quality products. The ensuing values allow for comparing various pesticides and pest management techniques, leading to solutions with less adverse effects on the environment [13-15].

The environmental impact quotient is a tool used to assess the environmental and health impacts of pesticide use in commercial agriculture. It helps growers make informed pesticide selection decisions, addressing issues such as farm worker safety, consumer well-being, wildlife preservation, and health. The environmental impact quotient has been used in integrated pest management projects across Asia since 2000. Following the determination of the pesticide's environmental impact quotient [16-18], the environmental effects of different pesticide treatments are compared by multiplying the pesticide's environmental impact quotient value by the application rate to compute the environmental impact.

This study aims to assess the risk levels associated with Chinese cabbage cultivation under insecticide resistance management strategies and two other farming practices to determine if adherence to insecticide resistance management can mitigate the environmental and health impacts of insecticide. The results could help governmental agencies implement enhanced insecticide resistance management programs in Thailand.

Carbon footprint estimates are also helpful in growing agricultural products, and these crop systems can be used to estimate greenhouse gas emissions in terms of carbon footprint [19, 20]. Nevertheless, it is important to promote insecticide resistance management techniques to encourage Thai farmers to cut back on greenhouse gas emissions. This study aims to determine whether the practice of insecticide resistance management can reduce greenhouse gas emissions into the environment. However, this is a pilot project to learn how farmers might use the proposed model. Therefore, the complete lifecycle of each method, including the carbon emissions associated with the production and transportation of insecticides, falls outside the scope of this study.

In this study, the carbon footprint and environmental impact on the Thamuang District, Kanchanaburi Province, Thailand, are evaluated to compare the different control strategies. The area under study is one of the most important for Chinese cabbage cultivation in Thailand. Intensive agricultural activities depend on the intensive use of insecticides, and there is a need for guidance to be provided to farmers, extension staff, and even policymakers on the environmental impact of insecticides to find cost-effective, environmentally safe ways of applying insecticide. This study presents some examples of less detrimental insecticide application methods for combating insect pests.

The results of this study may help government organisations in Thailand to execute improved insecticide resistance management initiatives. A research-based strategy, proven to be successful in controlling and preventing major pests while simultaneously addressing environmental issues, the practices used by farmers that exclusively involve the use of chemical insecticides to solve this problem. The goal of this study is to create a strategy for decreasing the use of pesticides with sustainable products, encouraging eco-friendly methods, and boosting the revenue of Chinese cabbage farmers in Thailand. The current study aims to evaluate the carbon footprint, environmental impact, efficacy, and benefit-cost ratios of Chinese cabbage grown via insecticide resistance management and farming methods to offer advice to farmers on how best to support sustainable pesticide use in the future.

2. MATERIALS AND METHODS

2.1. Field Description and Practice

The field experiment was performed from December 2022 to February 2023 in the Thamuang district of

Kanchanaburi Province, Thailand. This period was selected because it has suitable weather conditions for cultivating Chinese cabbage and, most importantly, a good irrigation system, meaning the land can be cultivated all year round. Three field experiments, each covering one acre (80 m in length x 50 m in width), were performed. The first experimental field implemented the insecticide resistance management method, while the second and third fields followed traditional practices, defined as farming methods 1 and 2.

Agricultural methods, including weed control, fertilisation, and the use of control agents for plant disease, were employed, depending on the practice of each farmer. In this study, pesticides were applied using a motorised backpack sprayer to control insect pests during the entire growing season for Chinese cabbage. Before the Chinese cabbage was harvested, the spraying procedure started fire days after germination with the installation of a fan nozzle. The sprayer was kept at an average spraying rate of 200 L/acre.

2.2. Design of Insecticide Resistance Management Program using the Windows Approach

Based on the data from the area, the key insects were found in the area as follows: the cabbage webworm (*Hellula undalis*), the diamondback moth (*Plutella xylostella*), and flea beetles (*Phyllotreta* spp.). Using the data acquired, insecticides were chosen following guidelines for using insecticides to control insect pests from Thailand's Department of Agriculture [21]. The data provide details about the common name, percentage of active ingredients, mode of action, application rate per acre, target insect pests, and long residue to control, as shown in Table **1**. We used the data from Table **1** to create a spray program based on the mode of action and following these guidelines: (1) applying insecticide with varying modes of action to subsequent insect generations; (2) rotating the modes of action after a period that corresponds with the target insect pest's generation time in its immediate habitat (also known as the "window"); and (3) developing complete, long-term prevention and control data to evaluate the efficacy of pest control [12, 22]. We developed our window method based on these standards, as indicated in Table **2**. Regarding the methods farmers used, they relied on their expertise and experience to select insecticides and carry out procedures (Table **2**).

2.3. Efficacy of Controlling Insect Pests and Marketable Produce

In this study, the Chinese cabbage was sprayed with insecticide five days after germination and continued until seven days prior to harvesting. In all trials, general observations were made prior to the first application to assess the relative infestation level of the target pest. The type and number of insect pests were systematically counted every five days in the experimental fields using the direct visual counting method. Under each treatment, 300 plants were examined and the number of insects per plant. The amount of marketable Chinese cabbage was evaluated cabbage at the harvesting period, according to the percentage of insect infestation. Samples from 200 Chinese cabbage plants were removed after each treatment process, using the criterion that if insects caused almost no damage to the lower leaf area (0–10%), Chinese cabbage could be sold as marketable produce [7, 23, 24].

2.4. Estimate of Greenhouse Gas Emissions and Environmental Impact

Based on the farm's actual per-acre use of insecticides in the field, various methodologies were used to compute greenhouse gas emissions. For the purposes of applying insecticides, energy-containing gasoline was determined. The amount of gasoline and insecticides used, along with the emission parameters given in Table **3**, are used to estimate the emissions. Lastly, the IPCC technique serves as the basis for the calculation [25].

Table 1. Details of insecticide treatments, including the common name, active ingredient percentage, mode of action, application rate, target insect pests and long residue to control in the experiment.

Treatments	Insecticide Common Name, Percentage of Active Ingredient	Mode of Action	Application Rate (g or litre per acre)[1/]	Target Insect Pests[2/]	Long Residue to Control (days)
Insecticide resistance management method	Fipronil 5% SC	2A	0.5	DBM/FB	5
	Chlorfenapyr 10% SC	13	0.5	CW/DBM	5
	Tolfenpyrad 16% EC	21	0.5	CW/DBM/FB	7
Farming method 1	Fipronil 5% SC	2A	0.5	DBM/FB	5
	Emamectin Benzoate 1.92% EC	6	0.5	CW/DBM	5
	Chlorfenapyr 10% SC	13	0.6	CW/DBM	5
Farming method 2	Acetamiprid 20% SP	4A	0.3	FB	5
	Emamectin Benzoate 1.92% EC	6	0.5	CW/DBM	5
	Chlorfenapyr 10% SC	13	0.6	CW/DBM	5

Note: [1/] CW = Cabbage webworm, DBM = Diamondback moth, [2/] Calculation based on spray volume at 200 L per acre.

Table 2. Details of windows approach of insecticide resistance management method and two farming methods.

Treatments	Timing of Application (Days after Planting), Frequency used and Spray Interval										Total Spray Application
	5	10	15	20	25	30	35	40	45	50	
Insecticide resistance management method	Fipronil twice (5-day interval)		Tolfenpyrad twice (7-day interval)				Chlorfenapyr twice (5-day interval)				6
Farming method 1	Fipronil + chlorfenapyr six times (5-day interval)						Chlorfenapyr + emamectin benzoate three times (5-day interval)				9
Farming method 2	Acetamiprid + emamectin benzoate six times (5-day interval)						Chlorfenapyr + emamectin benzoate three times (5-day interval)				9

Table 3. Carbon footprints and environmental impact (EI) per acre of insecticide resistance management method and two farming methods (including raw material and gasoline for applying insecticide).

Treatments	Production (Raw Material and Gasoline)	Emission Factors[1/]	Emission Sources kg (CO_2e/acre)	Emission Sources kg (CO_2e/kg of Chinese Cabbage)	EI per Acre
Insecticide resistance management method	Fipronil	13.4 kg CO_2e/kg	13.93	0.0034	4.41
	Chlorfenapyr	13.4 kg CO_2e/kg	13.93	0.0034	4.37
	Tolfenpyrad	13.4 kg CO_2e/kg	13.40	0.0033	3.75
	Gasoline	0.7 kg CO_2e/L	2.10	0.0005	-
Total	-	**43.36**	**0.0106**	**12.48**	
Farming method 1	Fipronil	13.4 kg CO_2e/kg	44.22	0.0103	14.12
	Emamectin benzoate	13.4 kg CO_2e/kg	20.90	0.0048	21.00
	Chlorfenapyr	13.4 kg CO_2e/kg	74.77	0.0175	1.01
	Gasoline	0.7 kg CO_2e/L	3.15	0.0007	-
Total	-	**143.04**	**0.0334**	**36.13**	
Farming method 2	Acetamiprid	13.4 kg CO_2e/kg	25.72	0.0060	11.49
	Emamectin benzoate	13.4 kg CO_2e/kg	62.71	0.0148	7.50
	Chlorfenapyr	13.4 kg CO_2e/kg	25.32	0.0059	2.86
	Gasoline	0.7 kg CO_2e/L	3.15	0.0007	-
Total	-	**116.9**	**0.0276**	**21.85**	

Note:[1/]Source from Agri-footprint5 and Thailand National Technical Committee on Product Carbon Footprint, 2015.

The environmental impact quotient (EIQ), a formula containing information about the effects of pesticides on human health and the environment, can be used to assist farmers in their choice of insecticides. The resulting EIQ values are then used to evaluate various insecticides and pest management strategies to determine which has a greater or lesser environmental impact. The pesticide's EIQ value describes how it affects consumers, farmworkers, and the environment. The EIQ values in this study were taken from the Cornell University Report 2018 [26]. Once the EIQ for the insecticides has been determined, Kromann *et al*. (2011) and Sande *et al*. (2011) suggest multiplying the EIQ value of the insecticides by the application rate to calculate the environmental impact and compare it with other insecticide treatments [17, 18]

In this study, information on the pesticide's common name, percentage of active ingredients, application rate (gram or litre per acre), frequency of use (number of applications per season), and use of gasoline for insecticide application (mL or L per acre) was recorded during the application of the actual insecticides in the field to estimate the greenhouse gas emissions and environmental impact using various methods.

2.5. Benefit-cost Ratio

Insecticide usage costs were recorded in three field experiments conducted during different seasons. The price of insecticide was calculated according to that charged by local shops selling pesticides. Throughout the study, labour costs were based on the existing wage for unskilled labour in the locality at the time of the study, equivalent to 300 Thai baht per acre per hour. At harvest time, plot yields were weighed and recorded. Chinese cabbage heads from each method were sorted into marketable and non-marketable produce, individually weighed, and sold at the prevailing price on the local market in Thai currency, baht (B). The benefit-cost ratio was computed using the procedures described in a study [7, 27].

2.6. Data Analysis

The emissions were estimated from the amount of insecticide used and fuel consumed in spraying based on these methods [28-30]. Greenhouse gas emissions were calculated using Eq. (**1**).

$$\text{Greenhouse gas emission} = \Sigma\,(\text{activity} \times \text{greenhouse gas emission factor}) \qquad \textbf{(1)}$$

Greenhouse gas emissions were calculated in every step by multiplying the emission factor of the material by the energy of that process (Equation 1) and recorded in terms of greenhouse gas emissions per product unit.

To calculate the environmental impact, dose, formulation, or percentage of active ingredients in the product, it is essential to determine the number of insecticide applications [17, 18]. The environmental impact formulation is presented below Eq. (**2**):

$$\text{Environmental impact per acre} = \text{EIQ} \times [\text{dosage acre}{-1}] \times \%\ \text{active ingredient x no. applications} \qquad \textbf{(2)}$$

In the context of dosage, it is measured in grams or litres per acre. The total environmental impact per acre was calculated by summing the environmental impact per acre/ha for each application in the season.

To determine the efficacy of insect pest control, the data on the number of insects were transformed into square root values {(X + 0.5)}, and comparisons between the mean numbers of insect pests using different methods were performed using the *t*-test (α = 0.05) to analyse the Chinese cabbage produced for the market via various methods.

The cost-benefit ratio of treatments was assessed based on net income. The net income of each treatment was calculated by deducting the total cost of the treatment from the gross returns. The total cost of production included both labour and insecticide charges.

Net income = Marketable produce × Market price – Total cost

The B: C ratio can be calculated by the following formula:

Benefit-cost ratio = Net income /total cost

Where BCR = Benefit-Cost Ratio

3. RESULTS

3.1. Estimate of Greenhouse Gas Emissions and Environmental Impact by using Environmental Risk Assessment *via* Various Methods

Table **3** shows the carbon footprints of the two farming methods and the insecticide resistance management method. While the emission factors of each insecticide are the same at 13.4 kg CO_2e/kg, differences in the frequency of insecticide use among the methods result in varying emissions per acre (CO_2e/acre) and emission sources kg (CO_2e/kg of Chinese cabbage), when comparing farming method 1 (143.04 CO_2e/acre or 0.0334 CO_2e/kg of Chinese cabbage) and farming method 2 (116.9 CO_2e/acre or 0.0276 CO_2e/kg of Chinese cabbage), both of which exhibit higher emissions per acre and per kg of Chinese cabbage. These figures were more than double compared to the insecticide resistance management method (43.36 CO_2e/acre or 0.0106 CO_2e/kg of Chinese cabbage). The results of the environmental impact are presented in Table **4** to compare the insecticide resistance management method with the two methods employed by farmers. For this comparison, data on the insecticides used, percentage of active ingredients, application rates of the products, and frequency of insecticide used were considered. As can be observed from Table **4**, for the insecticide resistance management method and the farmers' practices, the environmental impacts were low, specifically 12.48 in terms of the insecticide resistance management method. However, for both farmers' practices, the EIs were higher at 36.13 and 21.85 with farming methods 1 and 2, respectively, due to the increased application frequency and tank-mixed spray used by the farmers.

3.2. Efficacy in Controlling Insect Pests and Producing Marketable Produce

This study demonstrates that insect infestations are the biggest obstacle to growing Chinese cabbage within the allotted time. The problem was addressed by spraying insecticide nine times using the two farming methods and six times with the insecticide resistance management method. In assessing the different types and quantities of insect pests during the growing season and the percentage of marketable produce (Table **5**), adult flea beetles (*Phyllotreta spp.*), cabbage webworm (*H. undalis*), and diamondback moth (*P. xylostella*) larvae were all found to be regularly present. The average number of pests found when using the insecticide resistance management method equated to 1.20 ± 0.99, 0.68 ± 0.54, and 1.03 ± 0.80 insect/plant, respectively. When comparing these numbers with those of the two farming methods, no statistically significant difference was revealed. The average number of insects for each pest using farming method 1 was 1.18 ± 1.10, 0.75 ± 0.48, and 0.85 ± 0.82 insect/plant, respectively, and the average figures for each pest when employing farming method 2 were 1.09 ± 1.05, 0.65 ± 0.60, and 1.09 ± 0.75 insect/plant. After 52 days, the Chinese cabbage was harvested, and the results indicated no statistically significant differences between the three methods for marketable produce, ranging from 75.70 ± 14.50% to 80.50 ± 16.50%.

3.3. Benefit-cost Ratio

The total investment of 5,800 Thai baht for the insecticide resistance management method and labour expenses during the growing season was lower than that for farming methods 1 and 2, which equated to 9,552 and 6,992 Thai baht, respectively. The insecticide resistance management method showed the greatest value of 22.76 for the benefit-cost ratio, which measures the ratio of the overall yield cost to the sum of labour and pesticide costs. In contrast, the ratios for farming methods 1 and 2 were 14.02 and 19.84, respectively (Table **5**).

Table 4. Mean (±SD) number of insect pests and marketable produce (%).

Treatments	Mean(±SD) Number of Insect Pests			Marketable Produce (%)
	Diamondback Moth	Cabbage Webworm	Flea Beetles	
Insecticide resistance management method	1.20 ± 0.99	0.68 ± 0.54	1.03 ± 0.80	75.70 ± 14.50
Farming method 1	1.18 ± 1.10	0.75 ± 0.48	0.85 ± 0.82	80.50 ± 16.50
Farming method 2	1.09 ± 1.05	0.65 ± 0.60	1.09 ± 0.75	79.40 ± 13.80
T-Test	NS[3/]	NS	NS	NS

Note:[1/] NS = Not significantly different.

Table 5. Benefit-cost ratio of Chinese cabbage of insecticide resistance management method and two farming methods.

Treatments	Insecticide Price (Baht)	Labour[1/]	Total Cost (Baht/acre)	Marketable Produce (kg/acre)	Marketable Price (Baht/kg)[2/]	Net Income	Benefit Cost Ratio (B/C)
Insecticide resistance management method	4,000	1,800	5,800	12,530	11	132,030	22.76
Farming method 1	6,852	2,700	9,552	13,050	11	133,998	14.02
Farming method 2	4,292	2,700	6,992	13,250	11	138,758	19.84

Note:[1/] Calculation based on price and labour wage at 300 Thai baht/acre/time. [2/] Calculation based on farm price.

4. DISCUSSION

In summary, farming methods 1 and 2 resulted in triple the greenhouse gas emissions compared to the insecticide resistance management method. In addition, the insecticide resistance management method created much less environmental impact than both conventional farmer practices due to increased application frequency and tank-mixed spray employed by the farmers. According to a previous study, most Chinese cabbage growers prefer mixing multiple insecticides for insect control [12, 22, 31-33]. The findings of this study also revealed that farmers in the area frequently sprayed from a tank containing a mix of insecticides during the growing season. However, the principle of insecticide resistance management is to select insecticides based on life cycles, primary pest outbreaks, and long-lasting ability for control and prevention. For instance, flea beetles and diamondback moths are the main insect pests during the first 10 to 15 days following the planting of Chinese cabbage. Since Fipronil is effective against both insects, it is the best option during the initial window of insecticide application and eliminates the need to mix various insecticides.

Furthermore, because tolfenpyrad is effective against all three insects, it was used during the second growth stage of insecticide application (10–30 days after planting) when Chinese cabbage encountered infestations from all three insects. Table **2** shows that this selection permits a maximum of 7 days of effective control, but only two applications were permitted during that time. As a result, during the first month of the insecticide resistance method, the number of insecticide applications decreased to four compared with six used in the farming methods over the same period.

Chlorfenapyr was selected owing to its effectiveness against both pests during the third growth stage. This treatment began one month after planting and coincided with the main outbreaks of cabbage webworms and diamondback moths. Two applications are required, starting approximately 45 days after planting [22]. Compared to typical farmers who spray up to three times in a single interval and use different mixed insecticides each time, this deliberate method reduces the number of residual insecticides in the crop.

Moreover, there was no statistically significant difference in the efficacy of insect control regarding the number of insects detected or in the percentage of marketable produce upon using the three methods. This result aligns with earlier studies that evaluated the efficacy of rotation insecticide groups to control Chinese cabbage insect pests. These studies showed that compared with traditional spraying methods, this rotation could reduce the frequency of spray cycles by at least two times without affecting the insect pest population or causing plant damage [22].

The greenhouse gas emissions and environmental impact differed depending on the method used, with the figures from conventional agriculture being almost double those from insecticide resistance management due to the use of chemical insecticides and fossil fuels for insecticide application. These results accord with several studies which report that greenhouse gas emissions and environmental impact differ according to farm management methods, with conventional agriculture emitting almost twice as much as organic agriculture due to the use of chemical fertilisers and fossil fuels for tillage, herbicide, and insecticide application. Conventional farm management led to higher production per unit of planted area. Thus, it seems that conventional farming has a relatively higher carbon footprint than organic farming, although there is still room for both management practices to reduce their greenhouse gas emissions and environmental impact [34-37].

When Chinese cabbage yields from the two farming methods and the insecticide resistance management method were compared economically, the yield from the insecticide resistance management method was lower. However, because the insecticide resistance management method uses fewer insecticides and requires less labour for application, it exhibits higher values for net income and thebenefit–cost ratio (B/C).

The benefit-cost ratio measures the relative economic performance of treatments. When comparing a treatment to a control group, a ratio above one indicates the economic viability of the treatment [38-40].Benefit–cost ratios in this study ranged from 1: 22.76 to 1: 14.02, demonstrating the biological efficacy of the treatments and their returns on insecticide investments. In this study, the insecticide resistance management method was notably more economically viable than the farmer methods. Remarkably, all treatments hadbenefit–cost ratios greater than one, allowing farmers to select the most beneficial spray strategy. Thecost–benefit ratios calculated in this study are in close agreement with those previously published [7, 41].

The benefit-cost ratio is a useful metric, but before recommending it to farmers in the future, all relevant costs and benefits should be considered, including the potential long-term environmental and health impacts associated with insecticide use. It is also essential to consider the perspective from which these ratios are calculated (*e.g.*, the farmers' perspective or society as a whole).

The experiment revealed certain limitations concerning the use of a single test area, so it could not be used as a representation of the entire country. There were differences in climate, chemical base, and behaviour, as well as the level of resistance to local insecticides. This caused the model to vary depending on the context of the area. However, this experiment was a starting point, providing a model that extends the results of a large-scale field plot experiment. It also linked the environmental impact with the economic perspective for use as a point of attraction for farmers to turn into practice by recognising the importance of rotation in the use of an insecticide.

Only with widespread collaboration between the various stakeholders—cultivators, academic institutions, regulators, crop consultants, growers, and other end-users—can resistance management be successful. It is suggested that the government create a national decision-making organisation responsible for managing and monitoring pesticide resistance with expert assistance from the Department of Agricultural Extension on policy matters. This national decision-making body should meet every six months, with the Department of Agriculture submitting an annual pesticide resistance monitoring report for review to the board of this entity. This body would be responsible for decision-making and offering guidance on whether to replace or switch insecticides.

In line with earlier research on the impact of socioeconomic factors on farmers' perceptions of pesticides, wealthier farmers tend to use pesticides more frequently and inconsistently, believing that the best strategy for preventing insecticide resistance is to spray large amounts of mixed insecticides [42-47]. The use of products sharing the same mode of action as insecticides goes hand in hand with this mindset, indicating that farmers' technical product knowledge should come first. Furthermore, the effect of the retailer's expertise in the field should be considered, and the degree to which it influences the farmers' choice of product [48-52]. Policies and interventions should also be used to improve communication, considering educational attainment and behavioural patterns within the framework of cultural and contextual adaptations to favourably influence the usage of pesticides in rural areas. Regardless of the product's quality, farmers are likely to purchase insecticides based on affordability. It is anticipated that once quality is provided at a reasonable cost, consumer behaviour will shift towards the purchase of high-quality goods. It is imperative that farmers receive clear instructions on rotating insecticides with diverse modes of action to postpone the emergence of insecticide resistance in the region. In this regard, it would also be helpful if products were labelled with clear and easily understandable instructions to reduce their environmental impact [53].

CONCLUSION

The purpose of this study was to measure the effects of farming practices and pesticide resistance management strategies on the environment and carbon emissions. The outcomes demonstrate that the latter is both equally and more successful at lowering carbon emissions and having a positive environmental impact. Additionally, the insecticide resistance management method demonstrates a better benefit-cost ratio, considering both the labour costs and insecticide expenses, compared to the two farming methods. Nonetheless, it is imperative to recognise that this experiment is a foundational model, focusing on the economics, efficiency, and environmental aspects within the Thai context. However, to expand the experiment, it would be beneficial to explore and compare various sustainable farming practices, including organic farming, integrated pest management, and the use of biological control in the future. With respect to educational and policy implications, this study suggests the need for education on resistance management and continuous monitoring for its efficient use. This raises questions as to how these recommendations could be implemented in practice. Policymakers and extension services should play a crucial role in facilitating such education and monitoring efforts. In addition, for long-term sustainability, the results show that insecticide resistance management methods are more effective in terms of emissions and the benefit-cost ratio. It is important to assess the long-term sustainability of these methods. Resistance management strategies need to be adapted over time as pests evolve, and the study does not address this dynamic aspect. External factors potentially influencing Chinese cabbage farming should also be considered, such as market demand, climate change, and government policies. These factors can significantly impact the economic viability and environmental sustainability of farming methods.

LIST OF ABBREVIATIONS

CW = Cabbage webworm
DBM = Diamondback moth
FB = Flea beetle

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data and supportive information are available within the article.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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