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RESEARCH ARTICLE
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Environmental Impact Quotient, Efficacy and Economic Analysis of Insecticide Resistance Management and Farmer Practices in Chinese Kale in Thailand

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ABSTRACT

An evaluation of the environmental impact and cost-benefit performance of management strategies for Chinese kale cultivation was conducted in Thamuang District, Kanchanaburi Province, during the period from March to May 2024. The study compared an Insecticide Resistance Management (IRM) strategy with two conventional farming practices commonly adopted by local growers. Results indicated that the IRM approach significantly reduced both the Environmental Impact Quotient (EIQ) and field impact ratings, with values of 87.16 and 27.58, respectively, compared to the higher values observed under traditional farmer practices. The elevated EIQ values associated with conventional methods were primarily attributed to the frequent and intensive use of insecticides such as fipronil and related chemical compounds. A risk level analysis according to the EIQ field use rating revealed that the IRM strategy presented a low risk, while both farmer practices fell under the moderate risk category. An economic analysis of insecticide usage, labor costs, yield, and return on investment demonstrated that the IRM strategy involved significantly lower production costs (13,440 Thai baht/ha), representing a reduction of 22.75 to 32.59% compared to conventional farmer practices. The benefit-cost ratio, indicating the relationship between total yield value and combined insecticide and labor costs, was highest for the IRM strategy (13.32) compared to ratios of 10.72 and 9.45 for the two farmer groups, respectively.

Keywords: Chinese kale, Insecticide resistance management, Environmental impact quotient, Benefit-cost ratio, Pest management.

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INTRODUCTION

Chinese kale is an economically significant vegetable in Thailand due to its short harvesting period and high market value. According to the Department of Agricultural Extension (DOAE, 2024), Thailand cultivates approximately 5,680ha of Chinese kale, yielding 53,505 tonnes annually. As an economically significant vegetable, Chinese kale is cultivated year-round throughout the country to meet domestic consumption demands. The most serious insect pests affecting Chinese kale production are diamondback moth (*Plutella xylostella*), flea beetle (*Phyllotreta sinuata*), and cabbage webworm (*Hellula undalis*) (Kianmatee & Ranamukhaarachchi, 2007). Farmers frequently apply excessive chemical pesticides throughout the growing season to meet market demands for unblemished produce (Schreinemachers et al., 2012). In some cases, crops remain unharvested due to consumer preference for high-quality Chinese kale with pristine leaves free from pest damage. To achieve these standards, farmers resort to excessive applications of multiple chemical pesticides throughout the growing season (Kanjanamangsak et al., 2010; Harnpicharnchai et al., 2013; Schreinemachers et al., 2017; Naksen et al., 2022).

This excessive pesticide use has multiple detrimental consequences, including the disruption of beneficial insects, harm to non-target organisms, toxic residue accumulation in produce, human health risks, rapid development of pest

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resistance, and restricted export potential to international markets (Zafar et al., 2020; Zafar et al., 2022). These problems have been extensively documented in the scientific literature (Sukonthabhirom et al., 2009; Wanwimolruk et al., 2015 & 2016). Challenges arise from inadequate guidance, insufficient promotion of effective pest management, and limited access to new information, particularly regarding insecticide efficacy. To address these issues, Insecticide Resistance Management (IRM) principles offer a practical approach for delaying resistance development while reducing pesticide residue by employing efficient insecticides with different modes of action. IRM is founded on the principle of rotating insecticide groups with different action mechanisms to prevent pest resistance development (IRAC, 2025).

The Insecticide Resistance Action Committee (IRAC) categorizes insecticides into 37 groups based on their mode of action, emphasizing the importance of rotation among different insecticide groups to deter resistance development (IRAC, 2025). For rotation strategies to be effective, these insecticides must not exhibit cross-resistance to previously used compounds. Proper implementation of this approach yields economic benefits while meeting market demands for quality and safe production (IRAC, 2023a, 2023b; Palumbe, 2023).

When recommending chemical control options to farmers, both efficacy and environmental/health impacts must be considered. The Environmental Impact Quotient (EIQ), a formula developed to calculate the environmental impact of pesticides, provides valuable insights in this regard (Kovach et al., 1992; Kromann et al., 2011; Sampaothong & Punyawattoe, 2024). The EIQ was formulated to provide growers with information on the environmental and health implications of their pesticide choices, facilitating informed decision-making (Kovach et al., 1992; Levitan et al., 1995; Paez et al., 2013). This formula enables the calculation of the environmental impact of pesticides commonly used for fruits and vegetables (including insecticides, acaricides, fungicides, and herbicides) in commercial agriculture. The resulting values allow comparison between different pesticides and pest management strategies, ultimately identifying options with reduced environmental impact (Singh et al., 2007; Veettil et al., 2017; Sellare et al., 2020).

The EIQ methodology addresses numerous environmental concerns in agricultural systems, including farmworker safety, consumer well-being, wildlife protection, and broader health considerations. Since 2000, the EIQ has been employed in various Integrated Pest Management (IPM) projects across Asia, serving functions from impact assessment to pesticide selection (Paez et al., 2013; FAO, 2008; Prasopsuk et al., 2020a). The implementation of IRM strategies offers a promising approach to mitigating the adverse environmental and health impacts associated with conventional insecticide use in vegetable production. This study compares IRM methodologies with conventional chemical-dependent practices in Chinese kale cultivation in Thailand. By employing the EIQ assessment framework, this research quantifies and compares the ecological and health risks posed by different pest management strategies.

This investigation evaluates a scientifically validated approach demonstrating effectiveness in preventing and managing significant pests while addressing environmental concerns, contrasting it with conventional farming practices that rely exclusively on chemical pesticides. The EIQ impact assessment methodology illuminates the comparative risk levels associated with Chinese kale cultivation under IRM strategies versus traditional farming practices, thereby determining whether adherence to IRM strategies can effectively mitigate the environmental and health impacts of insecticide use. The objectives of this research are: 1) to estimate and compare the EIQ and EIQ field ratings between IRM and conventional pest management methods in Chinese kale production. 2) To evaluate and compare the efficacy and economic benefits of IRM versus conventional methods for Chinese kale production in Thailand. 3) To develop sustainable pest management protocols that reduce chemical pesticide usage, lower production costs, and yield high-quality produce in an environmentally responsible manner. 4) To provide evidence-based recommendations for farmers to promote sustainable insecticide use practices. 5) To generate data capable of informing governmental agencies in implementing improved IRM programs throughout Thailand's agricultural sector.

MATERIALS & METHODS

Field Description, Climatic Monitoring and Spray Application

This study was conducted at commercial Chinese kale farms in Thamuang District, Kanchanaburi Province, Thailand, from March to May 2024. The study area was divided into three sites, with two plots covering 1ha, under the following experimental design: Site 1 (Plot 1: 13°57'31.2"N 99°39'10.9"E and Plot 2: 13°57'32.5"N 99°39'12.3"E) implemented the IRM strategy, while Site 2 (Plot 1: 13°58'55.5"N 99°39'12.5"E and Plot 2: 13°58'56.7"N 99°39'14.0"E) and Site 3 (Plot 1: 13°59'33.9"N 99°38'49.8"E and Plot 2: 13°59'32.3"N 99°38'49.9"E) followed conventional agricultural practices, designated as Farmer site 1 and Farmer site 2, respectively (Fig. 1). Climatic monitoring was performed using the Extech 45160 data logger (Extech Instruments, Waltham, MA, USA). The data on the ambient temperature and relative humidity were recorded at 2m above the target areas. Insecticide applications began five days after germination and continued until seven days before harvest using a motorised knapsack sprayer at a spray volume of 500L/ha.

Details of Insecticide Application in the Experiment

Basic information relating to the area revealed an outbreak of the main vegetable pests on Chinese kale, consisting of three types: cabbage webworm (*H. undalis*), Diamondback moth (*P. xylostella*), and flea beetles (*P. sinuata*). The data obtained were used to select insecticides, following the recommendations for pesticide usage against plant pests (Colvin, 2010; IRAC, 2023a, 2023b; Palumbe, 2023). The information provided details on the effective substances, including common name, active ingredient (%), mode of action, and proposed pest control according to the insect type, application rate, and control duration (Table 1).

Table 1: Details of insecticide application in the experiments

Insecticides	Active ingredient (%)	Mode of Action	Propose to control[1]	Application rate (mL/20 liters of water)			Application rate (L/hectare)[2]			Duration to control
				IRM strategy	Farmer site 1	Farmer site 2	IRM strategy	Farmer site 1	Farmer site 2	
Chlorfenapyr	10% W/V SC	13	C and D	-	-	50	-	-	1.25	5
Emamectin Benzoate	1.92% W/V EC	6	C and D	-	-	50	-	-	1.25	5
Fipronil	5% W/V SC	2A	F	-	50	-	-	1.25	-	5
Indoxacarb	15% W/V SC	22	C and D	-	20	-	0.625	0.625	-	5
Tolfenpyrad	16% W/V EC	21	C, D and F	50	-	-	1.25	-	-	7

[1]C = Cabbage webworm, D = Diamondback moth, F = flea beetle [2]Calculation based on spray volume at 625L/hectare

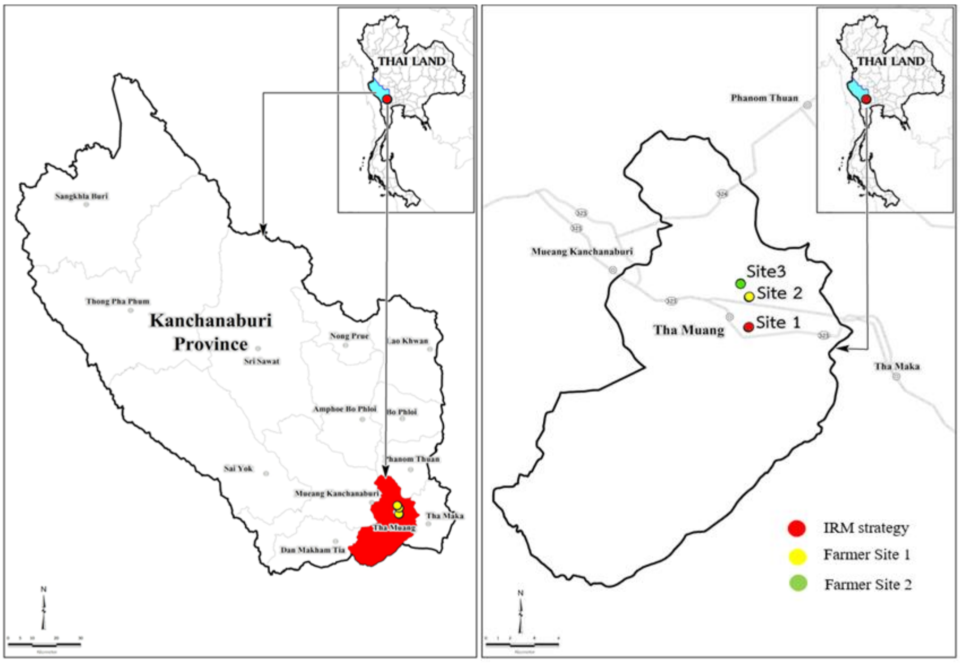

Fig. 1: Study areas involved in this experiment.

Developing an IRM Strategy

Information from Table 1 was extracted to establish a program for pesticide application, rooted in the mechanisms of action, by adhering to the following principles: 1) treating successive insect generations with diverse modes of action insecticides; 2) alternating modes of action after a duration that aligns with the target insect pest's generation time within its local environment (referred to as the 'window'); and 3) assessing the effectiveness of insect control by employing comprehensive, long-term prevention and control data (Sukonthabhirom et al., 2009; IRAC, 2023a, 2023b). Based on these criteria, a window technique was developed (Table 2). Farmers used insecticides and carried out actions based on their expertise and experience.

Environmental Impact of different Practices

The potential negative impacts of insecticide were evaluated using the Field Use EIQ adapted from the environmental impact quotient (EIQ) (Kovach et al., 1992; Cornell University, 2024). Based on measures of toxicity, exposure, and pattern of pesticide use, EIQ values can be used to assess the potential negative effects of pesticides on farm workers, consumers, and the environment. In this study, insecticide application data were collected according to the realistically used IRM strategy and farmer practices. Data regarding the insecticide's common name, active ingredient, percentage of active ingredient, application rate, frequency of usage, timing of application and area of treated plots were gathered from the experimental plots (Eshenaur et al., 2020; Grant, 2020; Sampaothong & Punyawattoe, 2024).

The environmental impact assessment was determined by the risk level, Field Use EIQ, calculated using the following formula:

Field Use EIQ = EIQ value × % active ingredient × application rate

The resulting values were classified into risk categories ranging from very low (<25), low (<50), moderate (50–99), high (100–199), and very high (> 200), providing a practical tool for comparing different strategies for pesticide use and supporting more environmentally sound pest management decisions (Kovach et al., 1992; Meys et al., 2024).

Efficacy of Insect Pest Control

Data were collected from 30 points, with 10 plants/points in an area of 10 m^2 randomly picked from the middle row of each plot before application, when the kale had two true leaves until the harvesting stage. Pre-spray counts were made immediately before spraying. Post-application counts were performed 24 hours after application. (Araya et al., 2023). A total of six sprayings with the IRM strategy and nine sprayings for both farmer practices were performed. The efficacy of insect pest control was evaluated using the data on the number of insects 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).

Table 2: Details of frequency used and timing of application of IRM and farmer practices in the experiments.

Treatments	Insecticides	Frequency used	Timing of Application	Timing of Application and purpose to control (Days after planting)									
				5	10	15	20	25	30	35	40	45	50
IRM strategy	Fipronil	2	5 days interval	D and F									
	Tofenpyrad	2	7 days interval			C, D and F							
	Indoxacarb	2	5 days interval							C and D			
	Total	6											
Farmer site 1	Fipronil+chlorfenapyr	6	5 days interval	C, D and F									
	Chlorfenapyr+indoxacarb	3	5 days interval							C and D			
	Total	9											
Farmer site 2	Fipronil+chlorfenapyr	6	5 days interval	C, D and F									
	Chlorfenapyr+emamectin benzoate	3	5 days interval							C and D			
	Total	9											

Benefit-cost of Each Management Strategy

Recording the quantity and quality of the produce harvested at 55 days old, the total fresh weight of the Chinese kale sold was measured from a 1ha area using both the IRM strategy and farmer practices, with the level of insect damage (quality of produce) also noted. Samples were collected from 200 Chinese kale plants and divided into two parts. One part was sold as Chinese kale from the lower leaf area damaged by insects (0–10% damage representing marketable yield), while the other part could not be sold due to the upper leaves and tender areas being subject to heavy insect damage (more than 50% representing unmarketable yield). The calculation of the benefit-cost ratio followed the methodology outlined in the research conducted by Greenway et al. (2023). The benefit-cost analysis of the test results comparing the marketable and unmarketable yields of Chinese kale produced in the market was performed using the t-test. The total insecticide and worker costs, revenue, and proportion of returns on investment were recorded. The test was conducted between trials that used the IRM strategy and those employing conventional agricultural methods.

RESULTS

Climatic Conditions during the Experiment

Meteorological data revealed a distinct seasonal progression from March to May. March exhibited moderate temperatures (27.9–36.1°C) with minimal precipitation (8.3 mm) and 65–70% relative humidity. April temperatures increased (29.7–38.1°C) with a modest rise in precipitation (17.7mm). May maintained similar thermal parameters (27.6–35.9°C) but demonstrated significant hydrological intensification (120mm precipitation) and elevated humidity (75–80%), indicating monsoon onset.

Environmental Impact Quotient (EIQ) and EIQ field rating

The EIQ scoring system for pesticides used in this experiment was based on the rating system developed by Kovach et al., 1992, relying on the EIQ and EIQ field rating systems to compare the IRM strategy with the methods employed by farmers (Table 3). This comparison analyzed the statistics on insecticides, including active ingredient percentages, application rates, and usage frequency. According to the IRM strategy and farmer practices, as can be observed from Table 3, the EIQ and EIQ field ratings were lower in the IRM strategy (146.77 and 27.81, respectively). However, for both farmer practices, the EIQ and EIQ field ratings were higher at 156.94 and 84.01 for Farmer Site 1 and 156.75 and 71.99 for Farmer Site 2, respectively, due to the increased frequency and tank-mixed spray applications performed by farmers. The results of the risk level analysis according to the EIQ Field Use Rating Levels demonstrated that the IRM strategy exhibited a low-risk level compared to both farmer practices, which fell under the moderate risk level category.

Efficacy of Insect Pest Control

The research results highlighted that insect pests posed the most substantial challenge to the cultivation of Chinese kale within the specified timeframe. This was addressed through insecticide spraying, conducted six times in the IRM strategy and nine times in the farmer practices. When evaluating the various types and numbers of insect pests across the growth season, along with the extent of plant damage (%) (Table 4), the larvae of the diamondback moth, cabbage webworm, and adult flea beetles were consistently present. Within the IRM strategy, the average pest counts per 30 sample points were 1.23±1.56, 0.84±1.20, and 1.30±1.47, respectively. These counts showed no statistically significant differences when compared with farmer practices. For Farmer Site 1, the average counts were 1.55±1.45, 0.92±1.95, and 1.00±1.04 for each pest type, while for Farmer Site 2, the averages equated to 1.35±1.30, 0.80±1.68, and 0.92±1.34 for each pest.

Benefit-cost of each Management Strategy

Chinese kale was harvested 50 days after planting. The percentages of marketable yield in IRM and farmer practices were not statistically significantly different. For the IRM strategy, the marketable yield was 72.82+14.21%. For Farmer site 1, it was 78.86+16.14%, and 76.42+13.29% for Farmer site 2 (Table 5).

When analyzing insecticide usage, labor costs, yield, revenue, and return on investment (Table 6), it was determined that the IRM strategy for controlling insect pests in Chinese kale exhibited a total production cost of 13,440 Thai baht/ha. This cost was notably lower than for farmers from both sites 1 and 2 by a margin of 22.75% to 32.59%. Moreover, when considering the benefit-cost ratio, which signifies the ratio of the total yield cost to the combined cost of insecticides and labor, the IRM strategy demonstrated the highest value at 13.32. In comparison, Farmer sites 1 and 2 showed ratios of 10.72 and 9.45, respectively.

Table 3: EIQ, EIQ field rating, and the risk level of IRM strategy and farmer practices in the experiments

Treatments	Insecticides	EIQ	Active ingredient (%)	Application rate (L/Hectare)	EIQ field rating	The risk level
IRM strategy	Fipronil	88.25	0.05	2.50	11.03	very low risk
	Tofenpyrad	27.33	0.16	2.50	10.93	very low risk
	Indoxacarb	31.19	0.15	1.25	5.85	very low risk
	Total	146.77	-	-	27.81	low risk
Farmer site 1	Fipronil	88.25	0.05	7.50	33.09	low risk
	Chlorfenapyr	37.50	0.10	11.25	42.18	low risk
	Indoxacarb	31.19	0.15	1.87	8.74	very low risk
	Total	156.94	-	-	84.01	moderate risk
Farmer site 2	Fipronil	88.25	0.05	7.50	27.58	low risk
	Chlorfenapyr	37.50	0.10	11.25	42.18	low risk
	Emamectin benzoate	31.00	0.0192	3.75	2.23	very low risk
	Total	156.75	-	-	71.99	moderate risk

Table 4: Average number of Chinese kale pests in IRM and farmer practices

Insect pests	Number of Insect pests/30 points			t – test
	IRM strategy	Farmer site 1	Farmer site 2	
Diamondback moth	1.23+1.56	1.55+1.45	1.35+1.30	NS[1]
Cabbage webworm	0.84+1.20	0.92+1.95	0.80+1.68	NS
Flea beetle	1.30+1.47	1.00+1.04	0.92+1.34	NS

[1]NS = Not significantly different.

Table 5: Percentage of marketable yield in IRM strategy and farmer practices

Types of yield	Percentage of marketable yield			t – test
	IRM strategy	Farmer site 1	Farmer site 2	
Marketable yields	72.82+14.21	78.86+16.14	76.42+13.29	NS[1]

[1]NS = Not significantly different.

Table 6: Economic analysis of Chinese kale in IRM strategy and farmer practices

Item	IRM strategy	Farmer site 1	Farmer site 2	% Decrease	
				VS Farmer site 1	VS Farmer site 2
Total insecticide and worker cost (C)[2]	13,440	19,940	17,400	32.59	22.75
Insecticide (Thai baht/hectare)	10,440	15,440	12,900		
Worker (Thai baht/hectare)	3,000	4,500	4,500		
Total yield cost (R)[3]	179,062.5	188,437.5	186,562.5		
Yield weight (kg/hectare)	11,937.5	12,562.5	12,437.5		
Average yield price (Thai baht/kg)	15	15	15		
Net income (Thai baht/hectare)	165,622.5	168,497.5	169,162.5		
Benefit Cost Ratio (R/C)	13.32	9.45	10.72		

[1]36.64 Thai baht = 1 US dollar; [2]Calculation based on price and labor wage in the area; [3]Calculation based on price at farm price.

DISCUSSION

The environmental impact and benefit-cost analysis revealed significant differences between the IRM strategy and conventional farmer practices in Chinese kale cultivation. The EIQ and EIQ field ratings demonstrated that the IRM strategy resulted in lower environmental impact compared to both farming practices. This difference can be attributed to several factors related to insecticide application strategies and practices. The EIQ field rating values obtained from the experiment revealed that the IRM strategy produced a lower environmental impact (27.81) compared to both conventional farming methods (84.01 and 71.99 for Farmer sites 1 and 2, respectively). These findings align with those reported by Sampaothong & Punyawattoe (2024), who found that insecticide resistance management methods resulted in significantly lower environmental impact compared to conventional farming methods in Chinese cabbage cultivation. Their study reported an environmental impact of 12.48 for IRM compared to 36.13 and 21.85 for conventional methods, demonstrating a similar pattern of reduced environmental impact when implementing IRM strategies.

The higher environmental impact observed in conventional farmer practices can be explained by the increased application frequency and tank-mixed spray applications employed by farmers, consistent with the findings of previous studies. Chaigarun & Nathapindhu (2006) reported that most Chinese vegetable growers preferred the combination of various insecticides for controlling insect pests in fields. Similarly, Prasopsuk et al. (2020a & 2020b) found that most Chinese kale growers favored mixing multiple insecticides to control insect pests, leading to higher environmental impact values.

This study demonstrates that implementation of the IRM strategy significantly reduced the environmental risk level from moderate (as observed in conventional farming practices) to low. This reduction is crucial from both ecological and human health perspectives, as noted by Kromann et al. (2011), who emphasized that the EIQ provides valuable information about the environmental and health repercussions of pesticide options, facilitating informed pesticide selection by growers. The IRM strategy employed in this study involved the selection of insecticides based on the main pest outbreaks, their life cycles, and long-lasting efficacy for prevention and control. This approach eliminated the need for multiple insecticide mixtures. For instance, during the early growth stages of Chinese kale (1–10 days after planting), when diamondback moths and flea beetles were the primary insect pests, fipronil was chosen for its effectiveness against both insects, thereby eliminating the need to mix different insecticides.

Additionally, during the second growth stage (10–30 days after planting), when Chinese kale encountered infestations from all three insects (diamondback moths, flea beetles, and cabbage webworms), tolfenpyrad was utilized due to its effectiveness against all three pests. This selection ensured successful control for up to seven days (Table 1), allowing only two applications during this timeframe. Consequently, the frequency of insecticide use was reduced to four applications within the initial month using the IRM strategy, in contrast to conventional farming methods, which involved six applications within the same period.

Furthermore, during the third development stage (one month after planting), when initial infestations of diamondback moths and cabbage webworms occurred, indoxacarb was selected for its efficacy against both pests. This necessitated only two applications, extending to approximately 45 days after planting. This approach minimized residual insecticides in the produce, distinguishing it from conventional practices where farmers performed up to three sprays during the same interval, employing different mixed insecticides on each occasion (Sukonthabhirom et al., 2009; Sampaothong & Punyawattoe, 2024).

These findings corroborate the research by Rahaman & Stout (2019), who evaluated the efficacy of next-generation insecticides against rice yellow stem borer. Their study found that chlorantraniliprole 0.4% G, which employs a similar targeted approach as the IRM strategy in this research, showed the highest efficacy in reducing pest infestations and increasing yield compared to conventional insecticides. Additionally, chlorantraniliprole demonstrated the lowest toxicity to natural enemies, highlighting the ecological benefits of targeted insecticide application.

In comparing the economic analysis of Chinese kale using the IRM strategy versus conventional farming practices, the results of this study show that although the yield achieved through the IRM approach was marginally lower than that of conventional methods, the overall economic benefits were significantly higher. The IRM strategy demonstrated a total production cost of 13,440 Thai baht per ha, notably lower than the farmers' costs at both Sites 1 and 2 by 22.75% to 32.59%. This cost reduction primarily stemmed from decreased insecticide application frequency and, consequently, reduced labor costs. The benefit-cost ratio (BCR), serving as an indicator of the relative economic performance of treatments, was highest for the IRM strategy at 13.32, compared to 10.72 and 9.45 for conventional farming sites 2 and 1, respectively. These findings align with research by Amoabeng et al. (2014), who reported that the strategic application of botanical insecticides in cabbage production resulted in higher BCRs compared to conventional methods, primarily due to reduced input costs.

Similar economic benefits of strategic insecticide application were reported by Mkindi et al. (2021), who found that extracts of pesticidal plants not only reduced pest damage but also enhanced plant growth, resulting in improved yield and economic returns. Additionally, Sampaothong & Punyawattoe (2024) demonstrated that their IRM approach for Chinese cabbage resulted in a BCR of 22.76, compared to 14.02 and 19.84 for two conventional methods, further supporting the findings of this present study on the economic advantages of IRM strategies. The higher BCR observed in the IRM strategy can be attributed to several factors, including reduced insecticide costs, lower labor requirements, and maintaining comparable marketable yields. This suggests that the IRM approach offers a more economically sustainable option for farmers, as indicated by Arbabtafti et al. (2012) & Ngbede et al. (2014), who emphasised that BCRs exceeding one denote the economic viability of treatments compared to conventional approaches.

The findings of this study have important implications for sustainable agriculture practices and policy development. The IRM strategy offers a balanced approach that addresses multiple sustainability dimensions: environmental (reduced EIQ), economic (improved benefit-cost ratio), and social (potentially reduced health risks from pesticide exposure). From a policy perspective, these results suggest that promoting IRM principles through extension services and farmer education programs could yield significant benefits. However, as noted by Timprasert et al. (2014) & Uesugi et al. (2021), challenges arise from a lack of proper guidance and the insufficient promotion of effective pest management practices. Addressing these gaps through targeted training and knowledge dissemination could enhance the adoption of IRM strategies among smallholder farmers.

Furthermore, as emphasized by Kovach et al. (1992) & Levitan et al. (1995), providing farmers with comprehensive information on the environmental and health implications of pesticide choices can facilitate more informed decision-making. The integration of EIQ assessments into extension services could serve as a practical tool for comparing different pest management strategies and identifying options with lower environmental impact. While this study provides valuable insights into the comparative efficacy, environmental impact, and economic benefits of IRM versus conventional practices, several limitations should be acknowledged. First, the study was conducted in a specific agroecological zone, and results may vary across different regions and farming systems. Future research should explore the applicability of IRM strategies across diverse agroecological contexts. Second, this study focuses primarily on EIQ and economic indicators, with limited consideration of broader ecological impacts, such as the effects on biodiversity and soil health. Future investigations could incorporate more comprehensive ecological assessments to provide a more holistic understanding of sustainability implications. Third, the cultural, social, and knowledge-based factors influencing farmers' pesticide use decisions are not extensively explored in this study. Research by Schreinemachers et al. (2017) and Amekawa et al. (2021) highlight the importance of understanding farmers' perceptions, knowledge, and attitudes towards pesticide use in promoting sustainable pest management practices. Further research into these socio-cultural dimensions could inform more effective strategies for promoting IRM adoption among smallholder farmers.

Conclusion

The IRM strategy substantiates its efficacy by manifesting lower values in both the EIQ and EIQ field ratings than conventional farming methods. Moreover, the IRM approach outperforms in terms of the benefit-cost ratio, signifying the amalgamation of total yield cost with the expenses of insecticides and labor, in contrast to the two groups of conventional farmers. However, it is paramount to acknowledge that this experiment serves as a pioneering model that addresses the environmental impact, efficiency, and economic dimensions in the context of Thailand. Fostering awareness among farmers about resistance management and its ecological implications remains an essential endeavour. Additionally, implementing on-field trials holds promise for enhancing the learning experiences of farmers. Given the variability in insect susceptibility to insecticides, continuous monitoring is indispensable for effective resistance management. Consequently, models may require refinement according to the specific regions and seasons. Regular updates on such information are pivotal in establishing a recommended window approach for farmers.

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Data Availability: All the data is available in the article.

Ethics Statement: This study did not use animals or humans; thus, no ethical approval was required.

Author's Contributions: Sonthaya Sampaothong: Writing – original draft, Writing – review & editing, Investigation, Methodology. Pruetthichat Punyawattoe: Data curation, Visualization, Investigation, Methodology.

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