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Research article

Policy options for promoting wider use of biopesticides in Thai agriculture

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ABSTRACT

Biopesticides are rapidly growing in importance for crop protection globally, but nearly all growth is happening in high income countries. No previous work systematically analyzed how lower-income countries can better benefit from the increased availability of biopesticides, which is important because these countries are particularly affected by the adverse effects of chemical pesticide use. Here we review the legislation of biopesticides in Thailand and combine this with stakeholder interviews and interview data from 300 smallholder farmers producing rice, fruit, vegetables, and flowers. We find that Thailand has adopted a biopesticide registration system that facilitates a fast-track registration, but it is still relatively costly considering the small market size. While 65 % of the sampled farmers used biopesticides, most farmers still heavily relied on conventional pesticides as their main method to control pests. Education, farming experience, positive attitudes of biopesticides, adoption of other integrated pest management methods and contacts with government extension agents were positively associated with biopesticide use. Coordinated action is needed to stimulate the supply of a wider range of biopesticide products while promoting adoption among farmers.

1. Introduction

The use of pesticides in agriculture is important to protect crop production from pests and diseases and competition from weeds, but the use of pesticides is associated with early mortality among farmers and farm workers, environmental pollution, loss of biodiversity, and health risks to consumers [1,2]. The global use of pesticides has increased rapidly, particularly in many lower-income countries where pesticides are weakly regulated, regulations are poorly enforced, farmers have limited knowledge about correct use, and markets are flooded with cheap pesticide products [3–5].

The problem is substantial in Southeast Asia, and particularly in high-value production systems producing flowers, fruits, and vegetables. It has been observed that the higher a crop's expected profit, the higher the quantity of pesticides applied [6] because farmers use pesticides as an insurance mechanism to protect against potential losses by spraying preventively [7]. Pesticide expenditure in excess of the economic optimum for key vegetable crops has been estimated to be 96 % for Vietnam, 92 % for Cambodia, 42 % for Laos [8], and 78–79 % for Thailand [7]. These previous studies [7,8] showed that the adoption of biopesticides is associated with

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less overuse, which suggests that the promotion of biopesticides is an effective strategy to abate pesticide overuse.

Biopesticides are naturally occurring substances that control pests (biochemicals), microorganisms that control pests (microbials), semiochemicals, enzymes, plant extracts, and other products [9]. Most biopesticides have a low impact on human health or the natural environment as these are naturally occurring substances derived from plants, animals, and microorganisms [10]. The popularity of biopesticides has increased as the use of chemical pesticides has become more restricted, countries have set ambitious policy targets for organic agriculture, the regulatory approvals of biopesticides have been streamlined, and farmers increasingly appreciate the benefits of biopesticides [11–13]. The global trade in biopesticides has grown from about US$ 1 billion in 2005 to US$ 3.2 billion in 2019 and is forecast to grow to US$ 4.2 billion in 2024 [14]. In comparison, the global market value for chemical pesticides is US$ 84.5 billion/year [15]. However, nearly all growth in the biopesticide market is happening in high-income countries (Europe, North America, Australia), not in lower-income countries.

This study focuses on Thailand as one Southeast Asian country with high levels of agricultural pesticide use [16–18]. In Thailand, the use of chemical pesticides[1] [19] has rapidly increased over the past 25 years [20]. Thailand imported around 98,260 tons of chemical pesticides in 2020, worth 29.3 billion Thai baht (about US$ 945 million) [21]. Herbicides account for about 70 % of this amount [22]. Problems of pesticide overuse and incorrect use have adversely affected the health of millions of Thai farm workers, have polluted soils and water, degraded ecosystems, and have raised serious concerns among consumers about the safety of the food they eat [18,20].

There has been an intense social debate in Thailand for the past 10 years about the role of pesticides in agriculture. The debate focused on a ban on three major pesticides: the herbicides glyphosate and paraquat, and the insecticide chlorpyrifos, but also more widely about the role of chemical pesticides in Thai agriculture. Paraquat and chlorpyrifos were banned in July 2020 while the use of glyphosate was restricted to certain crops [23] and is expected to be phased out soon. Opponents of the pesticide ban have pointed out that there are few alternatives to these pesticides available in Thailand and that farmers are left with no choice. Biopesticides, as alternatives to chemical pesticides are, indeed, still not widely available in Thailand. In 2020, Thailand imported microbial biopesticides worth 44.4 million Thai baht (US$ 1.43 million) and pheromones worth 5.6 million baht (US$ 0.18 million) [21], although some biopesticides are also manufactured locally.

The low use of biopesticides raises the question of whether Thailand, and other developing countries, are benefitting enough from the increased global availability of biopesticides and, if not, how these products can be made more available and accessible to Thai farmers. A sound understanding of the biopesticide sector is important to advise policymakers on how to make Thai agriculture more sustainable for the benefit of farmers, consumers, the environment, and exporters of agricultural products. Against this background, the study objective is to identify options for wider use of biopesticides in Thai agriculture by analyzing farmers' acceptance and attitudes toward these products and analyzing the regulatory framework governing the registration of new biopesticides.

2. Data and methods

2.1. Data

Data on pesticide production, trade, and product registration were collected through a review of existing data, written policies, laws, and regulations. We particularly studied whether pesticides and biopesticides are treated differently in legislation despite their different health and environmental risks. We also compared the situation in Thailand with that in the European Union, Australia, and the United States, which are leading in terms of global biopesticide adoption, to understand the enabling environment for wider biopesticide use.

Primary data were collected through a structured questionnaire survey in Thai of 300 farmers producing rice (115 samples), vegetables (98 samples), fruit/flowers and other crops (87 samples) (Table 1). The provinces of Nakhon Pathom, Pathum Thani, Supanburi, Ratchaburi, and Ayutthaya were selected for data collection. Situated near the capital city of Bangkok, these provinces have a particular market-oriented and intensive form of agriculture. Supanburi and Ayutthaya are important rice-growing areas. Nakhon Pathom and Pathum Thani are important for vegetables and flowers and Ratchaburi is a key fruit-growing province.

Data were collected in June 2022. Survey sites were selected in consultation with the Department of Agricultural Extension (DOAE) and the Provincial Agricultural Office (*Kaset Changwat* in Thai). We identified the main crops based on the cultivated area in each province and then identified districts, subdistricts, and villages where these crops were produced. We randomly selected up to ten farms per village for interviewing. In addition, a meeting was held with stakeholders (plant protection association, private sector, government agencies, and academics) to get their opinions about the use of biopesticide products.

Prior to data collection, all field research protocols were reviewed and approved by the Institutional Review Board of the University (KUREC-SS65/066).

2.2. Methods

The adoption of new technologies is usually modeled using discrete choice models in the literature with recent examples including [24,25], and [26]. The following discrete choice model for biopesticides adoption was postulated for this study with covariates

[1] Chemical pesticides are defined here as any synthetic chemical substance or mixture of substances intended for preventing, destroying, repelling, or mitigating any pest (adapted from Ref. [19]).

Table 1
Sample distribution by production system and province, 2022.

Province	Rice	Vegetables and flowers	Fruits and Sugarcane	Total
Supanburi	42	3	5	50
Nakhon Pathom	15	39	16	70
Pathum Thani	6	30	23	59
Ayutthaya	49	20	1	70
Ratchaburi	3	6	42	51
Total	115	98	87	300

selected based on previous studies as shown in equation 1.

$BIOPEST_{it} = f$ (gender, age, farm experience, land, perceived risk, biopesticide attitude, IPM practices, health awareness, pesticide knowledge, participation in group, extension, agro-shop, village head) (1).

The dependent variable BIOPEST takes the value 1 if farmer *i* at times *t* uses biopesticides and zero otherwise. The model is estimated using logistic regression as it fits an S-shaped adoption curve based on the theory of innovation diffusion [27] as well as earlier studies [28]. The estimated coefficients are expressed as marginal effects. Covariates and their hypothesized effects are explained in Table 2.

2.2.1. Behavioral and attitudinal factors

Perceived risk is a measure of a farmer's willingness to tolerate risk for loss of yield from pest or disease outbreaks, and ranges from 0 (completely unacceptable) to 10 (completely acceptable). Hence, a higher score indicates a greater willingness to take risk.

Biopesticides attitude is a measure of farmers' opinions and attitudes towards biopesticides. We measured with a set of eight statements: (1) biopesticides are an important input in crop cultivation; (2) biopesticides are more expensive than chemical pesticides; (3) the use of biopesticides does not reduce the need for chemical pesticides; (4) biopesticides are more difficult to use than chemical pesticides; (5) biopesticides are generally effective against crop pests and diseases; (6) biopesticides do less damage to the environment than chemical pesticides; (7) there is less resistance buildup when using biopesticides than when using chemical pesticides; and (8) crops sprayed with biopesticides are safe to eat. Five of these indicate a positive attitude (1, 5, 6, 7, 8) and the other three indicate a negative attitude. Answers were recorded on a three-point rating scale (3 = agree, 2 = unsure, 1 = disagree). The answers for negative attitudes were reverse coded so that a higher score means a more positive attitude toward biopesticides. The average rating was calculated.

IPM practices were calculated as the number of integrated pest management practices adopted by farmers. We used a list of five practices: (1) conserving natural enemies; (2) regularly monitoring plots for insect pests and diseases; (3) using chemical pesticides only if necessary; (4) spraying chemical pesticides to prevent pests; and (5) prefer chemical pesticide as a more effective way to control pests. The first three represent positive behavior while the other two represent negative behavior and were inversely coded. We summed up the number of positive IPM behaviors, which ranged from 0 to 5.

Health awareness is a measure of farmers' awareness about health issues related to chemical pesticides (we assumed that biopesticides were considered not to be harmful). It was measured using five statements on the perceived association between pesticides and health outcomes, namely chemical pesticides cause: (1) cancer, (2) infertility, (3) affect the respiratory system, (4) penetrate to skin, and (5) enter through the eyes. Answers were coded either as 1 (respondent thinks it is true) or 0 (not true). We summed the values into a score ranging from 0 to 5 with a higher value indicating more health awareness.

Pesticide knowledge indicates farmers' knowledge of how pesticides are usually applied. It was measured using a set of 5 statements

Table 2
Description and expected impact of variables included in the model.

Factors	Description	Expected effect
1) Individual and farm characteristics:		
Gender	Gender of household head (1 = Male, 0 = Female)	+,
Age	Age of household head (years)	+
Education	Education level of household head (years)	+
Farm Experience	Years of farm experience of the household head (years)	+
Land	Area of the farm (*rai* with 1 rai = 0.16 ha)	
2) Behavioral and attitude factors		
Perceived risk	Willingness to risk yield from pest outbreaks (score 0–10)	+,-+
Biopesticides attitude	Opinion and attitude towards biopesticides (score 1–3)	+
IPM practices	Use of integrated pest management practices (score 0–5)	+
Health awareness	Farmers' awareness about health issues related to pesticides (score 0–5)	+
Pesticide knowledge	Farmers' knowledge of pesticides (score 0–5)	
3) Social factors		
Participation in groups	Number of groups the farmer is a member of within the community (number)	+
Extension officer	Pest management advice from agricultural extension officer (score 0–4)	+
Agro-shop	Pest management advice from agro-shop (score 0–4)	+
Village head	Pest management advice from village head (score 0–4)	+

on pesticide use: (1) farmers choose pesticides by asking shopkeepers; (2) farmers buy chemical pesticides based on generic names; (3) farmers know the toxicity of chemicals by looking at the color code on the label; (4) farmers mix chemical pesticide together; and (5) farmers use the amount of pesticide as indicated on the label. Answers were coded either as 1 (correct answer) or 0 (incorrect answer). The answers for incorrect practices (1, 2, 4) were reverse coded. We summed the values into a score ranging from 0 to 5 with a higher value indicating better knowledge.

2.2.2. Social factors

Participation in groups: The number of groups a farmer is a member of within his or her community (number).

Extension officer: Frequency of obtaining pest management advice from an agricultural extension officer. Respondents were asked to select one of five options (0 = never, 1 = rarely, 2 = sometimes, 3 = often, 4 = very often). A higher score indicates more advice from extension officers.

Agro-shop: Frequency of obtaining pest management advice from an agro-shop. Respondents were asked to select one of five options (same as above). A higher score indicates more advice from agro-shops [29]. showed that farmers in Southeast Asia getting advice from agro-shops used more chemical pesticides.

Village head: Frequency of obtaining pest management advice from the village head in the community. Village heads are elected positions in Thailand. Respondents were asked to select one of five options (same as above). A higher score indicates more frequent advice from the village head.

3. Results and discussion

This section first analyzes the regulatory framework governing the registration of new biopesticides, and then analyzes farmers' acceptance and attitudes of biopesticides including factors associated with greater use of biopesticides.

3.1. Enabling environment

The legal framework regulating the production, import, sale and use of biopesticides is described to compare the enabling environments for biopesticide development in Thailand as compared to the United States, the European Union (EU), and Australia. Key enabling factors for biopesticide development are favorable registration conditions and policies promoting use.

In Thailand, the Department of Agriculture (DoA) has played a key role in promoting the production, application, and registration of biopesticides. The DoA has transferred technology to produce biopesticides (especially *Bacillus thuringiensis* or *Bt*) to the private sector for commercialization. However, domestic production does not meet farmers' demand for biopesticide as a substantial quantity is imported each year. In 2005, the total production of *Bt* and *Steinernema siamkayai* from local private companies was approximately 20 tons, while 27.7 tons of biopesticides were imported. Local production of biopesticides especially *Bt* has gradually increased [30]. In addition, DoA supports biopesticide development with infrastructure and legislation. For instance, a pilot factory was established for producing *Bt* and Nuclear Polyhedrosis Virus (NPV) [30].

In Thailand, the registration of biopesticides usually takes 18–24 months (Table 3). The time for registration is like that in the United States and Australia and slightly faster than in the EU. The DoA realized the importance of a fast registration process and has taken measures to shorten it further. The registration of biopesticides previously required product analysis, toxicology, and efficacy evaluation, but the DoA has exempted minimum risk biopesticides from toxicology tests. The list of minimum-risk biopesticides was expanded from 5 to 17 in 2021. The DoA also introduced a fast-track registration authorization for biopesticides in 2020 by establishing specific review committees and prioritizing the processing of biopesticide registration. These measures can shorten the registration process to 6–12 months for minimum-risk pesticides [31].

In the EU, the registration system for biopesticide is based on a system primarily established for the registration of chemical pesticides [32]. The registration of biopesticides in the EU requires toxicological and environmental testing and efficacy evaluation. During 2000–17, 47 new biopesticides were registered in the EU. The registration involves an evaluation of the active substance and an evaluation of the plant protection product. The first takes 15–16 months to complete and the second takes an average of 20–21 months, though both can be done in parallel under specific circumstances [33]. Approvals are valid for 15 years for low-risk substances and 10 years for other substances [33].

In the USA, biopesticides are recognized to have a lower risk than chemical pesticides. The registration process for biopesticides therefore generally requires much less data than for chemical pesticides [32]. Like in the EU, both the active substance and the formulated plant protection product are evaluated. Authority rests with the Environmental Protection Agency (EPA). The registration process usually takes 18–24 months. The applicant must submit documents to the EPA for approval after which its Biopesticides and Pollution Prevention Division (BPPD) has up to 19 months to reach a registration decision [33]. There is an exemption for minimum-risk pesticides and applicants are allowed to apply for a waiver based on published literature or their data. The US government also supports the biopesticide industry through research and development grants to provide data for biopesticides registration [34]. The Biopesticide Industry Alliance (BPIA), a group of private companies, fosters product innovation and regulatory processes by promoting industry standards for biopesticides and communicating the value of biopesticides.[2]

[2] http://www.biopesticideindustryalliance.org/.

Table 3
Registration procedure of biopesticides.

Items	Thailand	United States	European Union	Australia
Registration system for specific biopesticides	Yes	Yes	Yes	Yes
Central authority for biopesticides registration	Yes	Yes	No	Yes
Main authority involved	DoA	EPA	EFSA	APVMA
Registration cost compared to pesticide registrations	Lower	Lower	Lower	Higher
Registration procedure period (months)	18–24	18–24	30–42	15–24
Risk assessment for human health and the environment	Yes, with exemption or data waiver for toxicology test of minimum risk biopesticides	Yes, with exemption or data waiver for toxicology test of minimum risk biopesticides	Yes, with exemption or data waiver for toxicology test of minimum risk biopesticides	Yes, with no exemption or data waiver for toxicology test of minimum risk biopesticides
Registration period (years)	6	15	10–15	N/A

Notes: DoA = Department of Agriculture; EPA = Environmental Protection Agency, EFSA = European Food Safety Authority; APVMA = Australian Pesticides and Veterinary Medicines Authority.
Sources: own compilation

In Australia, the basic requirements for registration of biopesticides are the same as for chemical pesticides, including a comprehensive package of data on toxicology, efficacy, storage and to some extent field residues [35]. The Australian government and the Australian Pesticides and Veterinary Medicines Authority (APVMA) recognize the need to improve the regulatory system for novel products, including biopesticides. The registration process for biopesticides has been reviewed to facilitate faster registration.

A key difference between Thailand and the other locations is that the use of chemical pesticides is more strictly regulated and enforced in high-income countries, which stimulates farmers' demand for biopesticides. For instance, in Australia, the Australian Pesticides and Veterinary Medicines Authority (APVMA) has conducted systematic reviews of chemical insecticides and withdrawn many of them because of concerns about the disruption of natural enemies and this removal has stimulated biopesticide use [36]. In the EU, national initiatives to promote the use of biopesticides have been implemented [36]. Examples are Belgium's Program for Reduction of chemical pesticides and the Netherlands' initiative "Gewasbeschermingsmiddelen van Natuurlijke Oorsprong Effectief Gebruiken (GENOEG)". Another key difference is that while registration is costly, the EU and US offer very large markets for selling biopesticides, which reduces the relative cost of product registration [13]. In Thailand, registration is relatively costly as the market for biopesticides is much smaller. Another factor is that registration is valid for only 6 years in Thailand, but for 15 years in the United States and for 10–15 years in the EU.

3.2. Farm-level use of biopesticides

3.2.1. Socio-economic characteristics of the sample

Of the 300 sampled farmers, 34 % were women, indicating the important contribution of women to farm production in peri-urban areas of Bangkok (Table 4). The average respondent was 58 years old, which is consistent with national data showing that most Thai farmers are 40–59 years old. Farm households had 2.1 members on average and had about 26 years of farm experience. The average farm size was about 4.68 ha (ha). However, vegetable farmers were smaller at about 1.76 ha, which is similar to what was reported by Ref. [37]. The average size of fruit farms was 6.33 ha and that of rice farms 5.91 ha.

Of the sample of 300 farmers, 87 % used chemical pesticides as their main pest control method. Farm households also used other pest control methods such as biopesticides, and insect control such as adjusting the growing environment, preventing pests using inorganic substances, collecting, burning, or destroying crop residues, preventing and eliminating pests using various herbal extracts, and crop rotation.

3.2.2. Biopesticide use

Biopesticides are used by 65 % of farm households in the sample (Table 5). Products commonly applied included Trichoderma, *Bt*, Beauveria, *Metarhizium anisopliae*, and *Bacillus subtilis* (*Bs*). Although the use of biopesticide is safer for both farmers and consumers, the use of biopesticide is very low and limited to certain groups of farmers. Key obstacles identified through interviews with stakeholders include:

1) Farmers have limited knowledge about the benefits, methods of use, and active characteristics of biopesticides.
2) There are limitations to the methods of use, such as the type of pest, time of use, and location of spraying that limit wider adoption.

Table 4
Average socio-economic characteristics of the sampled farmers, 2022.

Characteristic	Rice	Vegetables and flowers	Fruits and sugarcane	Total/Avg
Households in the sample (n)	115	98	87	300
Female household head (proportion)	0.33	0.35	0.35	0.34
Age (years)	59.09	56.02	58.36	57.87
Education (years)	7.04	8.44	8.55	7.94
Full-time farm labors (persons)	2.13	2.19	2.09	2.14
Farming experience (years)	33.04	20.31	24.14	26.30
Farm size (ha)	5.91	1.76	6.33	4.68

Table 5
Use of biopesticides classified by crop type in Thailand, 2022.

Households	Rice		Vegetables and flowers		Fruits and sugarcane		Total	
	No.	Prop.	No.	Prop.	No.	Prop.	No.	Prop.
Using biopesticides	82	0.71	65	0.66	48	0.55	195	0.65
Not using biopesticides	33	0.29	33	0.34	39	0.45	105	0.35
Total	115	1.00	98	1.00	87	1.00	300	1.00

Note: No. = Number of observations; Prop. = Proportion.

3) The cost of applying biopesticides, especially labor cost, is high and higher than for some chemical pesticides. This affects farmers' profits and discourages adoption.
4) Biopesticides are specific to certain pests, which is a good thing, but it necessitates using a range of different biopesticides. Yet, the number of available biopesticides is small as compared to the number of pest species.
5) There are technological limitations to the production of biopesticides in Thailand such as lack of the stock of microorganism species, no good species of microorganisms, lack of method to collect microbial strains, no biobank, etc.

3.2.3. Factors associated with biopesticides use among farmers

Variables affecting farmers' decision to use biopesticides are shown in Table 6 as marginal effects. Marginal effects represent the change in an outcome from a one-unit change in the predictor. For dummy variables this is the change from 0 to 1.

The pseudo R^2 indicates that the independent variables included in the model can explain about 24.3 % of the variation in biopesticide use. The output returns a chi-square value (Hosmer-Lemeshow chi-squared) and the p-value is less than 0.05, meaning that the model is a good fit and the overall model is significant.

The main results are as follows. In terms of individual and farm characteristics, the marginal effect for education shows that one additional year of education increases the probability of using biopesticides by 2.7 %. The effect of years of farm experience is positive but not significant. The effect of education is consistent with a study on the adoption of biological control among rice farmers in northern Iran [26], though that study also showed experience to be significant. The results therefore suggest that higher educated farmers are more likely to adopt biopesticides.

Table 6
Logit model explaining the use of biopesticides among Thai farmers, 2022.

Predictor	Marginal effect		Z	p-value
Gender (1 = male, 0 = female)	0.0401		0.60	0.547
Age (years)	0.0032		0.89	0.372
Education (years)	0.0265	***	2.74	0.006
Farm experience (years)	0.0038		1.53	0.126
Land (rai)	−0.0005		−0.96	0.339
Perceived risk (level)	−0.0674	**	−2.23	0.026
Biopesticides attitude (score)	0.0234	**	1.97	0.049
IPM practices (score)	0.0675	**	2.24	0.025
Health awareness (score)	0.0474		0.98	0.326
Pesticide knowledge (score)	0.0492		1.62	0.106
Participation in groups (# of groups)	0.0743	*	1.86	0.063
Advice from ag extension (score)	0.1139	***	4.48	0.000
Advice from agro-input shop (score)	0.0359		1.37	0.170
Advice from village head (score)	−0.0579	**	−2.34	0.019
Rice	0.1362	*	1.91	0.056
Vegetable	0.1289	*	1.80	0.072
pseudo R^2	0.2425			
chi-square value	94.22***			

Note: *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Behavioral and attitude variables also have positive and significant effects on biopesticide use, which is consistent with previous studies [38,39]. A one-unit increase in farmers' positive attitude toward biopesticides is associated with a 2.3 higher probability of using them. The use of one more IPM practices (excluding the use of biopesticides) by the average farmer is associated with a 6.8 % higher probability of using biopesticides. This shows that farmers apply biopesticides as part of a wider IPM package rather than a stand-alone input. So, IPM training is important to expand the use of biopesticide in Thailand.

Farmers' participation in groups increases their probability of using biopesticides by 7.4 %. Also, getting advice from an agricultural extension officer increases the probability of biopesticide use by 11.4 % for the average farmer in the sample. This finding is consistent with results reported by Ref. [40] who showed that training increased the tendency of farmers to adopt biopesticides. On the other hand, our results show that advice from the village head had a negative and significant effect on biopesticide use (−5.8 %). It is possible that village heads are more likely to recommend a chemical pesticide. Agricultural extension officers could support the formation of farmer groups to extend the use of biopesticide in farming communities.

Rice and vegetable farmers tend to use more biopesticides than farmers growing other crops. A farmer growing rice has a 13.6 % higher probability of using biopesticides as compared to farmers growing fruits or sugarcane. Similarly, farmers producing vegetables have a 12.9 % higher probability of using biopesticides. This might be because available biopesticides in Thailand are more suitable for rice and vegetables [41].

In summary, there is still a lack of development and limited farm-level use of biopesticides in Thailand. Farmer acceptance and regulations limit the commercial production of new biopesticides. Regulations for registering biopesticides need to be improved as commercial registration and evaluation take a long time. In addition, the cost of biopesticide registration is high relatively to the size of the market. One way to update regulations to international standards is to organize an international workshop on the status of biopesticides in Thailand as compared to other countries. Thailand should promote cooperation in research between businesses, research institutes and government agencies to determine ways to improve biopesticide regulations.

The logit model indicates that the advice from agricultural extension agents, farmers' education, adoption of other IPM practices, attitude toward biopesticides, participation in groups, and growing rice or vegetables have a significantly positive effect on the use of biopesticides, which is consistent with other recent studies [26,38,39]. Our study shows that farmers have limited knowledge about the benefits of biopesticides, the methods of use, and active characteristics. Government support to enhance farmers' knowledge of biopesticides is an important first step to promote wider use. Wider use requires efforts from the government and private sector.

One limitation of this study is that farm-level samples were collected mainly from the peri-urban areas near Bangkok. Farmers in these locations are relatively market-oriented and may use a greater quantity of biopesticides (as well as chemical pesticides) than other farmers in the country. Future research could aim to take a sample that is representative for more farmers in the country. It would also be useful to record more details of the biopesticide products used.

4. Conclusion

Biopesticides are used by 65 % of farmers in central Thailand. While this appears high, we found that biopesticides were mostly used to complement the use of chemical pesticides rather than replace them. Farmers find it difficult to replace chemical pesticides with biopesticides for various reasons such as the perceived lack of effectiveness to control pests and lack of knowledge on pest management. Stakeholders further explained that as biopesticides are target-specific, farmers find that they do not provide a comprehensive solution to the many pests and diseases attacking their crops. The number of biopesticide products available on the market is also limited and there is a need to expand the range of products.

Our results show that greater use of biopesticides is positively associated with education of the household head and more positive attitudes toward biopesticides among farmers. Advice from extension services also had a strong and positive effect on biopesticide use, pointing at the importance of government promotion. This also reflects the experience in the EU, where some governments have initiated national programs to promote safe pest management. Therefore, adoption could be promoted through farmer training on the use of biopesticides, for instance by the Department of Agricultural Extension, universities, and farmer associations.

Thailand has enabled wider use of biopesticides by introducing a registration system that allows for a fast-track registration with fewer requirements than conventional chemical pesticides. However, the small biopesticide market size still makes it relatively costly for companies to register new products [42] as compared to large markets such as the US or the EU [33]. The Department of Agriculture and the Department of Agricultural Extension can support community-based enterprises to produce and sell biopesticides. The Department of Agriculture can also help the private sector to import a wider range of biopesticide products. If stakeholders were organized as an association, then this would help to coordinate and promote the development of the biopesticide industry, including research.

Supportive policies could promote both the supply of and demand for agricultural biopesticides. On the demand side, relevant agencies can enhance farmers' awareness and knowledge of biopesticides, especially through IPM training programs. On the supply side, relevant agencies can promote local availability of biopesticides by supporting community-based production while monitoring product quality and supporting the industry to make a wider range of biopesticides available in Thailand through imports as well as local research. The organization of stakeholders in an association would help to coordinate supply- and demand-side actions of the private and public sectors.

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Data availability statement

Data are available on request.

CRediT authorship contribution statement

Suwanna Praneetvatakul: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Supervision, Project administration, Funding acquisition. **Pepijn Schreinemachers:** Conceptualization, Methodology, Writing – Review & Editing. **Kampanat Vijitsrikamol:** Investigation, Writing – Review & Editing. **Chakrit Potchanasin:** Investigation, Writing – Review & Editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e24486.

Appendix

Table A1
Mean scores for variables used in Table 2

Characteristic	Mean	SD
Biopesticide use (=1)	0.65	0.48
Respondent gender (1 = male)	0.66	0.47
Respondent age (years)	57.87	10.53
Respondent education (years)	7.94	4.00
Respondent farm experience (years)	26.30	15.58
Farm size (rai)	29.24	49.02
Risk attitude (0–4)	2.40	1.05
Biopesticide attitude (8−24)	19.94	2.70
IMP practices (0–5)	2.92	1.20
Health awareness (0–5)	4.62	0.66
Pesticide knowledge (0–5)	2.99	1.04
Participation in groups (number)	1.35	1.17
Advice from ag extension (0–4)	2.23	1.41
Advice from agroinput shop (0–4)	1.63	1.25
Advice from village head (0–4)	1.45	1.41
Rice farmer (=1)	0.38	0.49
Vegetable farmer (=1)	0.33	0.47

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