Optimal strategy in controlling non-vector pest insect using green insecticide and mating disruption with cost-effectiveness analysis

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Abstract. Pest insect is one of the major pests that cause damage and loss in agriculture around the world. This threat also comes with other complex problems such as environmental hazards by the indiscriminate pesticide and the rapid development of insects due to the environmental change. Therefore, more environmentally friendly and sustainable control methods need to be implemented. This paper discusses a generic model to describe plant-insect interaction and focuses on the interaction between non-vector pest insect and plant. The model consists of a set of non-linear ordinary differential equations representing insect-plant predator-prey interaction with the addition of two controls, namely green insecticide and mating disruption. An optimal control approach was exploited to solve the control problem and find a set of control strategies that regulate the system optimally. The simulations were conducted for three strategies and four scenarios describing possibilities in the real-world application. Our results suggest that all strategies managed to prevent agriculture loss. A cost-effectiveness analysis was conducted to examine the cost and benefit of applying each strategy.

Keywords: Green insecticide, Integrated pest management, Mating disruption, Optimal control.

1. Introduction

The development of the agriculture industry has supported humanity for years. However, it also has caused many pest outbreaks worldwide. This development happens alongside the challenges of pests and plant diseases. The intensification of agricultural production creates new pest problem in many different ways such as creating a condition that is more suitable for pest to grow, the decrease of pest natural predator, and continuous source of food. In [36], it was shown that between the year 2001 and 2003, the animal pests caused loss were 7.9% for wheat, 15.1% for rice, 9.6% for maize, 10.9% for potatoes, 8.8% for soybeans, and 12.3% for cotton and based on [41], the loss percentages increased in the period between 2010 and 2014 associated to pests and diseases. The condition is getting even more complex because of climate change and global warming that can also affect the development of new diseases and the behavioural changes of pests. It is explained that climate change directly affects the biology of insect and it also affects the changing of
agricultural practices that leads to differences in host plants availability [40]. In [30], it is explained that climate change influences the intensification of all outbreak behaviour aspects for the cases of the pine beetle, gypsy moth, spruce beetle, and spruce budworm.

To deal with such serious challenges, farmers often use conventional indiscriminate pesticide to control the pest population. However, using indiscriminate pesticides also creates drawbacks such as more vulnerability and environmental damages in the long run [12]. One of the examples is in the case of Brazil which had 46% of active substance that comes with a medium to high risk to human due to the use of pesticide [11]. With such consideration, integrated pest management (IPM) is developed. IPM is the framework that a multi-disciplinary approach to minimize the economic, environmental, and health risks by integrating biological, chemical, and any other tools [1,6]. The benefit of implementing IPM for farmers is not only limited to increased productivity, but it also includes better control sustainability and lesser hazard to the environment that lead to better condition for long term agriculture [25].

Insects are one of the pests that contribute significantly to the loss of crop worldwide. Pest insect may damage crops by directly feeding on the crops and spreading pathogen that may create crop diseases. Non-vector pest insect is the type of pest insect that damages crops by only feeding on the crops. There are many species of insect that are categorized in this kind of insects. For example, there are about 450 species of aphid that damage crops by feeding on them [18], the larva of lepidopteran creates extensive damages by feeding on crops [22], locust is also considered as a major pest in China and India [35], and many more. Even with more actions to control the pest population, the trend of crop losses is still increasing [15]. This phenomenon of the increasing trend of pest density makes the development of integrated pest management strategy and optimization of the strategy becomes vital. In recent years, the cases of crop loss due to pest outbreak are still apparent and the existence of new pests is becoming an expensive threat [45].

The development of more eco-friendly control methods is made to give alternative methods for the use of indiscriminate pesticide. Bisacylhydrazine (BAH) insecticide is one of the innovations to the development of green insecticide that is more eco-friendly and was first developed in 1970 as insect growth regulator [48], and new synthesis is developed continuously [26]. This insecticide attacks insect when they are in larval stage by interacting with the ecdysteroid hormone that leads to improper development of larvae such as the improper development of mouthparts and the decrease of body weight that indicates less growth [10,13,14,43]. Since BAH insecticides disrupt specific development hormone of a certain larva, it does not possess a threat to the environment. For the mentioned reason, BAH insecticides are categorized as green insecticides [23]. The other control method is mating disruption. This method prevents the mating process of insects by repelling the sex pheromone from female insects with a synthetic sex pheromone [20]. The studies and the applications relating to mating disruption are done to increase productivity around the world. There are various ways to apply mating disruption. For examples, in [17], mating disruption was applied by combining it with a trap. In [5], mating disruption was applied using aerial dispensers. Researches have shown successful cases of mating disruption application for Planococcus ficus [7], Tuta absoluta [8], and Grapholita molesta [17].

2. Mathematical model

2.1. Model

The importance of the agriculture sector and the IPM approach as an alternative solution to deal with the challenges mentioned necessitates the development of mathematical models for the pest management system. Mathematical models play an important role in approximating, explaining, and predicting the phenomenon, then to analyse the possibility of interventions. Optimal control is one approach to strategize the best pest management program that maximizes the benefit and minimize the cost of the controls application. Various mathematical models cater the topics about pest insect and plant protection starting
with simple Lotka-Volterra predator-prey model to describe the pest-plant interactions such as what is explained in [32] to more complex models to explain more aspects of pest management. The model in [33] explained the role of pest insect as pathogen vector that may cause various plant diseases. The model in [29] explained the interactions of competing pests and their natural predator. In [28], a model that discusses two intraguild predation models with generalist and specialist kind of prey and predators. The model in [29] discusses the interactions between pests and their parasitoids as an alternative in biological control. The purpose of this paper is to formulate a model that describes the life stages of pest insect and its interaction to crops, then construct the model with controls and optimize the system using optimal control approach, so it may give the description of how to apply controls and what strategy is the optimal strategy.

Previous models have only explained the interaction of insect of plants without considering the life stages of the insect or considering only constant control in the model. Therefore, we proposed a new model to describe the life stages of insect, the interactions between insect and plants, and the use of dynamic control form and we gave the optimal control analysis. To construct the model in this paper, we adopted the model introduced in [2] that describes the life cycle of insects and the model introduced in [4] that describes prey-predator interaction between insects and plants. The new model we constructed uses five compartments that describe the population of insect and the measurement for plants and we referred it as IYFM-P model. This model is based on the two interactions found between insects and crops. The first interaction is prey-predator interaction in which the pest insects will feed on the crops [9]. The second interaction is that plants will be the most likely place for the insects to lay their eggs since it is the source of food for the insects [24]. We then introduced two control methods to the model namely BAH insecticide intervention and mating disruption. BAH insecticide intervention is represented by $\frac{\mu_I}{1+\mu}$ that can be interpreted as the proportion of the larva population that is affected by BAH insecticide. The mathematical form to describe mating disruption in [2] was modified. Mating disruption is represented by $\frac{\mu_F}{1+\mu}$ that can be interpreted as the proportion of the female population whose pheromone is repelled. The IYFM-P compartmental model is seen in Figure 1.

![Figure 1. IYFM-P compartmental model](image)

It is assumed that the population of insect can always be categorized to larva ($I$), unfertilized female ($Y$), fertilized female ($F$), or male insect ($M$). The larva grows to be a female with the possibility of $r$ and to be a male with the possibility of $(1 - r)$ with the rate of $\nu_I$. The female insect will be fertilized by a male insect with the rate of $\nu_Y$ and the possibility of mating $\min\left\{1, \frac{\nu_M}{Y}\right\}$ that describes two conditions namely male
abundance and male scarcity. The switch between the two conditions is written as \( \xi = \gamma M - Y \). Male abundance is a condition where \( \xi > 0 \) while male scarcity is a condition where \( \xi \leq 0 \). The fertilized female will lay eggs near the source of food with the intrinsic number of \( 18.4 \). The carrying capacity for larva is limited and this is expressed as \( 18.2 \). Male will be unfertilized female with the rate of \( 18.3 \). The crop can grow with the intrinsic number of \( 18.5 \) and grow logistically with the expression \( 18.6 \). Each compartment has a constant natural mortality rate. However, the mortality of plant is also influenced by the consumption rate of insects. The consumption rate of the insect is \( 18.7 \). Then the consumption caused mortality rate follows Holling type II that follows the expression of \( 18.8 \). The algebraic expression of the model is as follows.

\[
\begin{align*}
\frac{dI}{dt} &= b \left( 1 - \frac{l}{cP + m} \right) F - (v_I + \mu_I + \epsilon_I u_I)I \\
\frac{dY}{dt} &= r v_I I - (1 - \epsilon_2 u_2) v_Y Y - \delta F - \mu_Y Y \\
&\quad - (1 - \epsilon_2 u_2) v_Y Y - \delta F - \mu_Y F \\
\frac{dP}{dt} &= r_P P \left( 1 - \frac{P}{K} \right) - \frac{P}{m + P} (\alpha N - \mu_P P). \tag{5}
\end{align*}
\]

2.2. Control problem
System (1)-(5) includes two control instruments which are the use of BAH insecticide \((u_1)\) and the use of synthetic sex pheromone in applying mating disruption \((u_2)\). The control \( u_1 \) represents the proportion of the larva population that is going to be exposed to BAH insecticides. Since BAH insecticide is a green insecticide that disrupts the development of the insect’s larva and eventually kills the larva population, we assigned \( u_1 \) only to the larva compartment \((I)\). The use of synthetic sex pheromone in mating disruption is meant to decrease the transfer rate \( v_Y \) and prevent the unfertilized female to be mated and become fertilized female. Therefore, we assigned the control \( u_2 \) to the compartment of unfertilized female \((Y)\) and the compartment of fertilized female \((F)\) and we interpreted it as the proportion of female natural pheromone that is repelled by the synthetic sex pheromone. It is important to note that the interpretation of mating disruption in this paper is slightly different from \( Y_P \) in [2]. However, both interpretations of the mating disruption technique have the same implication to the system where if \( u_2 \) and \( Y_P \) increases, the transfer rate from \( Y \) to \( F \) decreases. Since all of the control functions are interpreted as proportion, bounded control policies are implemented. Thus, the controls are defined within the bounds

\[
\begin{align*}
0 \leq u_1 &\leq 1 \\
0 \leq u_2 &\leq 1. \tag{6}
\end{align*}
\]

for all points of time within the control period \( t \in [0, t_f] \) where \( t_f \) is the length of the control period. It is also assumed that each control function has its effectiveness which is denoted as \( \epsilon_1 \) and \( \epsilon_2 \) corresponding to \( u_1 \) and \( u_2 \) for \( \epsilon_i \in [0,1] \) \( i = 1,2 \). We then write the controls as a vector of control functions \( u(t) = (u_1(t), u_2(t), u_3(t)) \) and \( U \) is a set of all admissible control where

\[
U = \{ u | u_i(t) is Lebesgue measurable in [0, t_f], u_i(t) \in [0,1], t \in [0, t_f] \}. \tag{7}
\]

We then formulate the optimal control problem to find the possibilities of optimal strategies. The objectives of applying controls are to maximize the performance index \( J \) for the control period within \([0, t_f]\). We constructed an objective functional as follows:
\[
\max J = \int_0^T BP(t) - \left( C_1 u_1^2(t) + C_2 u_2^2(t) \right) \, dt
\]

for \( B \) and \( C_i; i = 1, 2 \) are balancing the cost weights. The first part of the objective functional is the size of plant density while the second part of the objective functional is the control effort. With the mentioned interpretation, it is intuitive to say that the objective of controls application is to maximize the size of plant density and minimize the control efforts to regulate the system in total. The optimal control approach is an approach to choose admissible control functions that optimize the objective functional. The maximization process was subjected to the system (1)-(5) that we referred to it as the state system. The behaviours of each state functions in the state system that we wanted to intervene are the responses to given control functions [46].

Since we had bounded Lebesgue measurable controls and non-negative initial values for the state system, bounded non-negative solutions existence to the system (1)-(5) was guaranteed. We also had a concave objective functional for control functions \( u_i \) in a set of admissible control \( U \), the system (1)-(5) is linear in respect to control functions and we had bounded control functions, thus the existence of optimal control was guaranteed [19].

### 3. Result and Discussion

#### 3.1 Optimality conditions

In this section, optimality conditions of optimal control problem were constructed. Pontryagin’s maximum principle explained in [42,46,47] was exploited to derive the optimality conditions. First, we construct a Hamiltonian function as follows.

\[
H = BP - \left( C_1 u_1^2(t) + C_2 u_2^2(t) \right) + \sum_{i=1}^5 p_i(t) \dot{x}_i(t)
\]

for \( p_i(t) \) are time dependant functions called adjoin functions corresponding to the state functions and \( \dot{x}_i \) are the right-hand side of the system (1)-(5). Based on Pontryagin’s maximum principle, the optimality conditions are derived from the following equations.

\[
\frac{\partial H}{\partial u_i} = 0; i = 1, 2
\]

\[
\dot{x}_i(t) = \frac{\partial H}{\partial p_i}; i = 1, 2, 3, 4, 5
\]

\[
p_i(t) = -\frac{\partial}{\partial x_i}; i = 1, 2, 3, 4, 5.
\]

The control problem also needs to satisfy the transversality condition expressed as equation (13) [42].

\[
(S_X - p)\delta X_{t_o,t_f} + (H + S_T)\delta X_{t_o,t_f} = 0
\]

for \( S(t) \) is scrap function. Condition (10) provided the optimal control pair for the control problem. It is important to note that the Hamiltonian function is piecewise, thus the optimal control can also be piecewise. The controls should also satisfy the bounds of the control. Considering these factors, the first optimal control is written as the following equation.

\[
u_1(t) = \min \left\{ 1, \max \left\{ \frac{e_{11} p_1}{2A_1}, 0 \right\} \right\}.
\]

The second optimal control is piecewise. If \( \xi > 0 \), the system enters male abundance condition and the optimal control is written as the following equation.
If $\xi \leq 0$, the system enters male scarcity condition and the optimal control is written as the following equation.

$$u_2(t) = \min \left\{ 1, \max \left( \frac{(p_2 - p_3)\varepsilon_2v_3y}{2A_2}, 0 \right) \right\}.$$  

(15)

Condition (11) provided the state system, which is the equations (1)-(5). Condition (12) provided the adjoin system. The adjoin system can also be piecewise because of the piecewise Hamiltonian function. The adjoin functions are written as equations (17)-(23).

$$\frac{dp_1}{dt} = p_1 b - \frac{F}{cP + m} + p_1 (v_1 + \mu_t + \varepsilon_1 u_1) - p_2 r v_1 - p_4 (1-r) v_1 + p_5 \frac{\alpha P}{m + P}$$  

(17)

$$\frac{dp_3}{dt} = -p_3 b \left( 1 - \frac{1}{cP + m} \right) - p_2 \delta + p_3 (\delta + \mu_F) + p_5 \frac{\alpha P}{m + P}$$  

(18)

$$\frac{dp_5}{dt} = 1 - p_5 \frac{cIF}{(cP + h)^2} - p_5 \left( \frac{2r_P P}{K} - \mu_P + \left( \frac{p}{(m + P)^2} - \frac{1}{m + P} \right) \alpha N \right).$$  

(19)

The expression for $\frac{dp_2}{dt}$ and $\frac{dp_5}{dt}$ are piecewise. If $\xi > 0$, the system enters male abundance condition and the functions are expressed as the following equations.

$$\frac{dp_2}{dt} = p_2 (\mu_F + (1 - \varepsilon_2 u_2) v_3) - p_3 (1 - \varepsilon_2 u_2) v_3 + p_5 \frac{\alpha P}{m + P}$$  

(20)

$$\frac{dp_4}{dt} = p_4 \mu_M + p_5 \frac{\alpha P}{m + P}.$$  

(21)

If $\xi \leq 0$, the system enters male scarcity condition and the functions are expressed as the following equations.

$$\frac{dp_2}{dt} = p_2 (\mu_F + \varepsilon_2 u_2) v_3 + p_5 \frac{\alpha P}{m + P}$$  

(22)

$$\frac{dp_4}{dt} = p_2 v_3 (1 - \varepsilon_2 u_2)(1 - \varepsilon_2 u_2) y + p_4 \mu_M + p_5 \frac{\alpha P}{m + P}.$$  

(23)

From (8), we see that the scrap function $S(x_i(t), r)$ is zero. It is also assumed that the terminal time $t_f$ is fixed and the terminal values of state functions $x_i(t_f)$, for $x_i \in \{I, Y, F, M, P\}$ are free. Therefore, the terms $S_x, S_t, \delta_t$, and $\delta_t$ became zero, and the remaining terms were written in (24).

$$p_i(t_f) = 0; i = 1, 2, 3, 4, 5.$$  

(24)

The control problem is analytically represented as the optimal controls, state system, and adjoin system. The adjoin system must satisfy the transversality condition (24). To solve the control problem, it is needed to find the solutions of the state system (1)-(5) and adjoin system (17)-(23) simultaneously.

### 3.2 Numerical solutions

In this section, we verified the analytical result from the previous section using a numerical experiment. By doing this, we can inspect the effects of the control measures in optimizing the performance index and state system. For the numerical simulation, we defined three control strategies that define the combination of control measures that will be applied to the system. These strategies are presented in Table 1. “On” means that the control is used in the strategy and “off” means the control is not used in the strategy.

We solved the problem using the infamous 4th order Runge-Kutta [34] and forward-backwards sweep method following the steps in [31] using GNU Octave 5.2.0. The initial values for the state functions and the parameters used in this paper are presented in table 2. The parameters used for the simulation are mainly collected from [2] and [4]. The values of the parameters are presented in Table 3.
Table 1 Control strategies

| Strategy | $u_1$ | $u_2$ |
|----------|-------|-------|
| No control | Off | Off |
| A | On | On |
| B | On | Off |
| C | Off | On |

Table 2 Initial values

| State functions | Initial values | Unit |
|-----------------|----------------|------|
| $I$             | 100            | insect |
| $Y$             | 400            | insect |
| $F$             | 120            | insect |
| $M$             | 100            | insect |
| $P$             | 100            | weight/area |

Table 3 Parameter values

| Parameter | Description | Value | Unit |
|-----------|-------------|-------|------|
| $b$       | The intrinsic number of egg-laying | 9.272 | 1/day |
| $r_p$     | The intrinsic number of crop growth | 5     | weight/area.day |
| $r$       | The ratio of female to male from the larva stage | 0.57 | - |
| $K$       | The carrying capacity for crops | 1000  | weight/area |
| $\gamma$  | The number of females that can be fertilized by a single male | 2 | Insect |
| $\mu_I$   | The natural mortality rate of the larva | 0.06667 | 1/day |
| $\mu_Y$   | The natural mortality rate of unfertilized female | 0.01332 | 1/day |
| $\mu_F$   | The natural mortality rate of fertilized female | 0.01332 | 1/day |
| $\mu_M$   | The natural mortality rate of male | 0.01157 | 1/day |
| $\mu_P$   | The natural mortality rate of crop | 0.0125 | weight/area.day |
| $c$       | The number of egg per unit mass per unit area | 1.5 | insect/(weight/area) |
| $m$       | The saturation constant | 0.8 | weight/unit area |
| $\alpha$  | The consumption rate of the larva | 0.3 | insect.day |
| $v_I$     | The growth rate from larva to mature insect | 0.0407 | 1/day |
| $v_Y$     | The mating rate | 0.5 | 1/day |
| $\delta$  | The rate of transfer from fertilized female to unfertilized female | 0.1 | 1/day |

We also defined four simulation scenarios with various combination of balancing cost weights that represents the cost of applying control efforts to mimic the possibility of the diverse cost of control application due to the production cost, availability of the substance, the distribution cost of the substance and the tools required, etc. By defining these scenarios, we are able to inspect the effectiveness of the control strategies in four different control scenarios. The control scenarios are presented in Table 4 and we set $B = 1$. The effectiveness of controls is assumed to be $\epsilon_i = 0.9$ for $i = 1,2$. 

7
Table 4 Simulation scenarios and descriptions

| Scenario | $C_1$ | $C_2$ | Description |
|----------|-------|-------|-------------|
| 1        | 5     | 5     | The cost for the application of both controls are relatively low |
| 2        | 15    | 15    | The cost for the application of both controls are relatively high |
| 3        | 5     | 15    | The cost for the application of BAH insecticide is relatively low and the cost of the application of mating disruption is relatively high |
| 4        | 15    | 5     | The cost for the application of BAH insecticide is relatively high and the cost of the application of mating disruption is relatively low |

Larva population dynamics in every scenario is seen in Figure 2.

3.2.1. Larva and male population
The dynamics of the larva population was observed in Figure 2. The larval population without control increased significantly from 100 to around 750 in the first few days of the control period. The population then decreased slowly to around 550. This happened due to the competition and the decrease of food resources from time to time. When control measures were applied, the population of the larva is less in number compared to the no control condition in any scenario. In all scenarios, Strategy A gave the most benefit. Comparing Strategy A between scenarios, the most significant result was generated in Scenario 1 and the least in Scenario 2. This is expected because Scenario 1 is the scenario where that has the least cost.
of control application compared to the other scenarios while Scenario 2 which has the highest cost of control application. Comparing Scenario 3 and Scenario 4, the result in Scenario 4 was more significant than the result in Scenario 3. This indicates that using mating disruption and BAH insecticide in the condition where the cost of its application is relatively low suppresses larva population better even when the cost of BAH insecticide application is relatively high compared to the case where BAH insecticide application cost is low and mating disruption application cost is high. On the last 20 days of the control period, there was a sudden increase in the larva population in every scenario. This happened because there was a sudden drop in BAH insecticide. The same phenomenon also happened for Strategy B for the same reason. Comparing Strategy B and Strategy C in every scenario, it is presented that Strategy B gave more significant result compared to Strategy C. This is intuitive when applying the control measures individually since Strategy B uses BAH insecticide and directly kill larva while Strategy C only uses mating disruption that affects larva population indirectly. It can be concluded that even if the condition without control had the decreasing trend for the larva population, it was still possible to make the population of larva lesser and Strategy A gave the most benefit in decreasing the larva population.

The dynamics of the male insect population is presented in Figure 3. The results of male population dynamics did not show a significant difference between scenarios. However, it is shown that Strategy A gave the most significant results in every scenario compared to the other three strategies while the least significant results were given by Strategy C. These results are consistent with the dynamics of larva population that are already presented in Figure 2. These results indicate that reducing the larva population is a key factor in reducing total insect population in general, proved by the decrease of the male population that was not directly controlled by any of the control measures. Thus, by reducing the insect population in general, the potential to prevent agriculture loss and the potential benefit become bigger.
3.2.2. Unfertilized and fertilized female

Unfertilized and fertilized female populations are the critical populations in regulating the whole system since these populations are the beginning of the new generation production. The dynamics of these populations are presented in Figure 4 and Figure 5. It was shown that the unfertilized female population increased when Strategy A or Strategy C was applied. This indicated the success of mating disruption in preventing mating process while the sudden population increase did not happen when Strategy B was applied. With that consideration, then we need to note that the effectiveness of the controls cannot be analyzed directly from these populations. However, we can see how each control works on the system. For the first few days in scenarios where the cost of BAH insecticide applications was low, the unfertilized population from the result of Strategy B increased and became bigger compared to the results of Strategy A. This doesn’t indicate that Strategy B prevents more larva production in the first few days. In the first few days of the control period, Strategy B resulted in a higher number of unfertilized female population because there were more unfertilized females from the larva population. Thus, Strategy A resulted with lesser number of unfertilized females because there was an active killing of the larva by BAH insecticide application. The population dynamics of the fertilized female population was directly affected by unfertilized female population dynamics. Strategy A resulted in the least fertilized female since it prevented mating for a longer amount of time and conducted alongside the application of BAH insecticide. Thus the population of fertilized female was suppressed from both mating disruption and BAH insecticide application and the system produced lesser larva and decrease the total population significantly. Without mating disruption, the population of fertilized female increased. However, Strategy B that uses BAH insecticide only managed to kill larva that will become unfertilized female and fertilized female. Thus, Strategy B suppressed the fertilized female population and made it lower compared to the condition where there was no control applied to the system. Unfertilized female population dynamics in every scenario is seen in Figure 4.

![Figure 4 Unfertilized female population dynamics in every scenario](image-url)
3.2.3. Plant density
The goal of applying control to manage the insect population is to prevent the loss of plant density. Plant density depends on the size of the insect population as the predator of the plant. The dynamics of insects furthermore affects the dynamics of the plant density. According to Figure 6 in which the plant density dynamics is presented, it was found that in all scenarios regardless of what strategy was implemented, the trend of plant density dynamics was decreasing. However, when the control measures were applied, the size of plant density increased. Strategy A gave the most significant benefit compared to the other two strategies while Strategy C gave the least benefit. Comparing Strategy A in Scenario 3 and Scenario 4, it was found that Strategy A in Scenario 4 gave better result compared to Strategy A in Scenario 2. This indicates that applying more mating disruption along with the application of BAH insecticide despite high application cost for mating disruption is more effective in preventing the loss of plant density compared to the condition where BAH insecticide application cost is low. However, mating disruption is not effective when it is the only control measure applied. This was shown and presented in Figure 6 that when mating disruption was applied individually, the result given was not significant and it was not optimal to implement more control without complementing control measure. This interpretation is also confirmed in [9,10].

Fertilized female population dynamics in every scenario is seen in Figure 5.

Figure 5. Fertilized female population dynamics in every scenario
Plant density dynamics in every scenario is seen in Figure 6.

![Plant density dynamics in every scenario](image)

**Figure 6.** Plant density dynamics in every scenario

3.2.4. The optimal controls
Finding the optimal controls to regulate the system is the main goal of the control problem and it relates closely to the implementation of strategies. Figure 7 presents the profile of the optimal controls for each scenario and each strategy. It was intuitively seen that when controls, especially mating disruption, will be implemented independently, the control effort should not be implemented fully. When the cost of application is low, it is suggested to apply BAH insecticide at full capacity only for the first 70 days of the control period and to apply mating disruption at full capacity only for the first 25 days of the control period. When the application cost is high, it is suggested to apply BAH insecticide at full capacity only for the first 5 days of control and to apply mating disruption only on the first day of the control period. After the mentioned day, the control efforts should be decreased and even decreased significantly for mating disruption. This is due to the lack of effectiveness for both control measures especially mating disruption that the benefit of applying more control is not worth the cost that will be spent. However, when BAH insecticide and mating disruption are applied together, the benefit that will be generated is worth the cost. This is suggested by Strategy A that even in Scenario 2 where both control costs are high, it is still suggested to apply BAH insecticide at full capacity for 50 days and mating disruption for 62 days. It can be concluded that BAH insecticide and mating disruption are complementing each other to control the insect population and prevent loss of plant density that its optimal control suggests using more of them when being used simultaneously compared to being used individually. Optimal controls profile in every scenario is seen in Figure 7.
3.3 Cost-effectiveness analysis

In the previous section, we have presented the numerical simulations for the optimal control problem and resulted in diverse strategies and scenarios. A cost-effectiveness analysis will be an important consideration in choosing what strategy to be used along with other considerations. In this section, we used two metricizes which were average cost-effectiveness ratio (ACER) and incremental cost-effectiveness ratio (ICER). ACER can be interpreted as the ratio between cost and benefit. In the case of epidemiology, ACER is the ratio between the total cost to apply intervention and the total infection averted [3]. ICER is defined as the difference in cost per difference of benefit for two competing strategies. In the specific case of choosing two medication alternatives, ICER is the incremental ratio of the difference of total cost for the alternatives and the incremental benefit commonly defined as quality-adjusted life-year (QALY) such as in [16] and [21]. In this paper, the benefit is defined as the total size difference of plant density given by each strategy in each scenario. Therefore, the total benefit of Strategy $i$ in Scenario $s$ for $i \in \{A, B, C\}$ and $s = 1, 2, 3, 4$ can be calculated with

$$\text{Benefit}(i, s) = \int_0^{t_f} B \left( P_{i,s}(t) - P_0(t) \right) dt$$  \hspace{1cm} (23)

for $P_{i,s}(t)$ is the size of plant density resulted from Strategy $i$ in Scenario $s$. The expression (23) represents the total loss that can be prevented by applying control measures. The total cost is defined as the efforts spent on a strategy. Total cost for Strategy $i$ in Scenario $s$ can be calculated with

$$\text{Cost}(i, s) = \int_0^{t_f} \sum_{k=1}^{2} C_k u_{k,i,s}^2(t) dt$$  \hspace{1cm} (24)

for $C_k$ is the balancing cost weight and $u_{k,i,s}$ is the optimal control from Strategy $i$ in Scenario $s$ resulted from the previous section as given in Figure 7. Note that in some cases, the $u_{k,i,s}$ can be zero following the strategies presented in Table 1. ACER and ICER calculations can be done using the following formulas.
\[ ACER(i, s) = \frac{\text{Cost}(i, s)}{\text{Benefit}(i, s)} \]  
\[ ICER(i, s) = \frac{\text{Cost}(i, s) - \text{Cost}(i - 1, s)}{\text{Benefit}(i, s) - \text{Benefit}(i - 1, s)} \]  
for \( i = 1, 2, 3 \). Cost\((0, s) = 0\) and Benefit\((0, s) = 0\) and we call these values as the cost and benefit in the condition without control. From (25) and (26), it is easy to see that ICER\((1, s) = ACER(1, s)\), and we can infer that ACER is the incremental cost-effective ratio comparing an alternative to the condition without intervention [37]. To conduct the calculation, we ranked the strategies in each scenario from the least beneficial the most beneficial strategy. After the strategies were ranked as provided in Table 5, we calculated the ACER and ICER following the steps provided in [38]. Based on the calculation, the results varied for each scenario. In scenario 1, the most cost-effective strategy was Strategy A with the last ICER values 0.351411 compared to Strategy C which was the second most cost-effective strategy with ACER value 0.489908. In Scenario 2 and Scenario 3, surprisingly, the most cost-effective strategy was Strategy C with ACER value 0.160912 while the second-best strategy in Scenario 2 and Scenario 3 was Strategy A with ICER value compared to Strategy C was 0.31606 and 0.358492 respectively. In Scenario 4, Strategy A was the most cost-effective strategy with the last ICER value 0.297647 compared to Strategy B which was the second-best strategy with ACER 0.45892. These results from the comparison using ICER is also consistent with the result using ACER by scanning the lowest ACER values for each scenario. From the results, we can conclude that strategy that generates the most benefit in scenarios with less cost of control application is not always the most cost-effective strategy.

The decision to choose one strategy over another in many cases does not depend only on one metric such as cost-effectiveness analysis. Therefore, another possible factor must be taken into considerations. One of the considerations is which strategy generates the benefit that is preferable for the strategy to be taken as the best option. In Scenario 1, as the most cost-effective alternative, Strategy A increased the size of plant density as much as 16.79% while Strategy C increased it as much as 1.01%. In Scenario 2 and Scenario 3, Strategy C as the most cost-effective strategy increased the plant density by 15.28% and 16.53% respectively. In Scenario 4, Strategy A as the most cost-effective strategy increased the plant density by 16.34% while Strategy B as the second-best strategy increased the plant density by 3.82%. The ACER and ICER calculations are shown in table 5.

Table 5 ACER and ICER calculations

| Scenario | Strategy | Benefit | Cost | ACER | ICER | ICER | ICER | ICER |
|----------|----------|---------|------|------|------|------|------|------|
| 1        | C        | 265.56  | 130.1| 0.489908 | 0.489908 | 0.489908 | ed   |
|          | B        | 1469    | 1169 | 0.795779 | 0.863275 | d     | ed   |
|          | A        | 4411.7  | 1587.1| 0.359748 | 0.14208 | 0.351411 | 0.359748 |
| 2        | C        | 40.171  | 6.464 | 0.160912 | 0.160912 | 0.160912 | 0.160912 |
|          | B        | 1004.1  | 460.81 | 0.458928 | 0.471348 | d     | d    |
|          | A        | 4013.9  | 1262.4| 0.314507 | 0.266327 | 0.31606 | ed   |
| 3        | C        | 40.171  | 6.464 | 0.160912 | 0.160912 | 0.160912 | 0.160912 |
|          | B        | 1469    | 1169 | 0.795779 | 0.813629 | d     | d    |
|          | A        | 4343.3  | 1549.1| 0.356664 | 0.132241 | 0.358492 | ed   |
4 Conclusion and Suggestion

The development of the agricultural industry necessitates the development of more environmentally friendly and more sustainable control methods. Thus, integrated pest management (IPM) is developed. This paper has presented one part of IPM which is the optimization of BAH insecticide and mating disruption as the alternatives of conventional indiscriminate pesticide. We constructed the control problem and solved it using the optimal control method. We have also simulated and observed the effects of BAH insecticide ($u_1$) and mating disruption ($u_2$) applications to the insect life cycle in preventing the loss of plant density in four different scenarios and three strategies namely Strategy A that used both BAH insecticide and mating disruption. We have also conducted a cost-effectiveness analysis using ACER and ICER. We found that the results generated varied from one scenario to another. In Scenario 1, Strategy A was the most cost-effective alternative and Strategy C was the second most cost-effective alternative. In Scenario 2 and Scenario 3, Strategy C was the most cost-effective alternative and Strategy A was the second most cost-effective alternative. In Scenario 4, Strategy A was the most cost-effective strategy and Strategy B was the second most cost-effective strategy. The effectiveness of each strategy in preventing the loss of plant density also varied between scenarios. In Scenario 1, the most cost-effective strategy generated 16.79% benefit while the second-best strategy generated a 1.01% benefit. In Scenario 2 and Scenario 3, the most cost-effective strategy generated a 0.15% benefit while the second most cost-effective alternative generated a 15.28% benefit and a 16.23% benefit respectively. In Scenario 4, the most cost-effective strategy generated a 16.34% benefit while the second most cost-effective strategy generated a 3.82% benefit.

From the simulation experiment, we can conclude that mating disruption is not significant in preventing plant density loss and decreasing insect population if it is applied individually, particularly when the effectiveness of mating disruption is not 100%. This is expected since mating disruption is an indirect intervention to decrease the larva population and the same conclusion also mentioned in [8] and [9]. The efficacy of mating disruption depends on the specific species of insect that we are dealing with, the amount of active substance, type of dispenser, and the frequency of application [44]. Therefore, when using mating disruption, it is suggested to apply other complementing control measures such as the application of BAH insecticide which kills larva directly.

This current work only deals with the interactions between non-vector insects and plants. We recommend further research to also include vector insect that spreads pathogens and diseases to plants. Other eco-friendly control methods such as the use of parasitoid, the use of mass trapping, and the introduction of insect natural predator can also be added to the model instead of just two control methods. Other representations of the control functions are also recommended such as the use of volume unit to represents the BAH insecticide and the synthetic sex pheromone. The results presented in this paper are the results of a theoretical study. Thus, it is recommended to validate the model through empirical data collected from a field or laboratory experiment.

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