Response Surface Optimization of Citronella Oil Encapsulation using Gum Arabic as Biopesticide

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Abstract

The use of chemical pesticides negatively impacts the environment, health, and ecosystems, necessitating safer alternatives such as biopesticides. This study aimed to determine the effects and optimal conditions of pH, temperature, and coating-to-oil ratio on the distribution and encapsulation size result. Encapsulation was done by dissolving, gum Arabic as coating agent in water and mixed at 50 °C. This solution was then combined with citronella oil and vigorously mixed. pH and temperature of the solution were adjusted to form microdroplets. Finally, a crosslinking agent was added to solidify the droplets, and they were further processed to remove air bubbles. Response Surface Methodology was employed to optimize the distribution and encapsulation size, resulting optimum conditions were achieved at pH 5, coating to oil ratio of 1.159:1 (gum arabic to essential oil, g/g), and a temperature of 55 °C. Efficacy tests revealed that citronella oil biopesticide killed 77.85% of *Spodoptera exigua* pests on day 3, compared to 55.85% in the control group without biopesticide. This study demonstrates the potential of citronella oil biopesticide as an alternative to chemical pesticides.

Introduction

Agriculture is a crucial sector in supporting global food needs and significantly contributes to the economies of many countries [1]. The ever-growing global population and the demand for agricultural products always increase significantly, which drives efforts to enhance productivity through the use of modern technologies and innovations in crop protection [2]. In order to support agricultural productivity, chemical pesticides have become essential in protecting crops from pests and diseases. Chemical pesticides are used to ensure maximum yields, reduce losses caused by pest attacks, and maintain the quality of agricultural products [3].

Although effective, excessive use of synthetic chemical pesticides has led to issues such as ecosystem imbalances, resistance in target organisms, and adverse effects on non-target species, including beneficial soil microorganisms and pollinators [4-6]. Moreover, pesticide residues can contaminate the environment and pose risks to human health [7]. Therefore, there is a need for natural-based pesticide alternatives to replace synthetic chemical pesticides [8,9].

Citronella oil, derived from citronella grass (*Cymbopogon nardus*), has significant potential as a natural biopesticide. Active compounds such as citronella, geraniol, and citronellol exhibit effective pesticidal properties against various agricultural pests and pathogens [10-12]. Furthermore, citronella oil is a natural resource, making it more environmentally friendly than chemical pesticides. However, citronella

oil has a high volatility, causing it to evaporate quickly under ambient conditions and making it susceptible to degradation [13]. This limits the effectiveness and shelf life of biopesticide products based on citronella oil. Its low stability poses a significant challenge to its application in agriculture.

Encapsulation is a promising technology that can address the limitations of citronella oil. This technology enables citronella oil to be coated with protective materials, enhancing its stability and controlling its release [14]. Additionally, encapsulation protects against degradation caused by environmental factors [15]. Coacervation is one of the most effective and economical encapsulation techniques for citronella oil. This method involves forming microcapsules through interactions between coating materials, such as gum arabic and citronella oil [16-18]. Coacervation is conducted under relatively simple environmental conditions, making it suitable for industrial-scale applications [19].

Previous research has extensively explored the encapsulation of essential oils for various applications. For instance, a study by Manaf *et al.* [13] demonstrated that encapsulating citronella oil using gum arabic resulted in an encapsulation efficiency of 94% and enhanced the stability of active ingredient release with a Fick's law diffusion coefficient of 0.5. Another study by Pujiastuti *et al.* [20] showed the stability of citronella oil encapsulated with β-Cyclodextrin, achieving an encapsulation efficiency of 90% and improving the stability of the active ingredient by 85%. However, despite these promising results, there has been no specific research focusing on the encapsulation of essential oils as biopesticides. Therefore, research on the encapsulation of citronella oil as an agricultural biopesticide using a systematic approach through process optimization remains very limited and requires further exploration.

Optimization for achieving uniform distribution and particle size in biopesticide encapsulation is essential for maximizing the biopesticide's stability, handling properties, efficacy, and for minimizing its environmental impact. It allows for a more controlled and predictable delivery of the active ingredient, leading to better pest management outcomes. This study focus in only investigates the effects of process variables, including pH, the ratio coating to oil, and operating temperature, on the encapsulation size distribution (Polydispersity Index) and encapsulation size (Z-average) of the encapsulated products. This study employs Response Surface Methodology (RSM) to optimize the encapsulation process of citronella oil. RSM is a statistical method to determine the correlation between a response and a set of input variables. This method is time-saving and cost-effective to describe the influence and interaction between input variables on the response [21]. The results of the RSM analysis obtain optimal process conditions for the response and polynomial mathematical equations that are useful for larger scale production. The results of this study are expected to support the development of more stable, effective, and environmentally friendly citronella oil-based biopesticides, contributing to sustainable pest management practices.

Material and methods

Material

The materials used in this study include citronella oil obtained from a local attire farmer in Kendal. Gum arabic (Acacia arabica exudate) was from Sigma-Aldrich. Acetic acid (CH_3COOH, 100%), sodium hydroxide (NaOH, 100%), and sodium tripolyphosphate (STPP, 98%) were purchased from Merck, Germany.

Methods

The coating solution was prepared by dissolving gum arabic, weighed according to formulation (1, 2, and 3 gum arabic to essential oil, g/g), into 100 mL of distilled water and homogenized at 500 rpm for 30 min at 50 °C. The essential oil emulsion was formed by mixing the coating solution with 1.5 g of citronella oil and homogenized at 20,000 rpm for 3 min. For coacervation, the acidity of the emulsion was adjusted using 3.5 M CH_3COOH to the desired value and stirred at 500 rpm for 30 min at the specified temperature. After storing at 10 °C for 30 min, 20 mL of 3% sodium tripolyphosphate solution was added as a crosslinker, followed by homogenization at 20,000 rpm for 3 min. The pH was then adjusted to 9 using 5 M NaOH, and the emulsion was further homogenized at 20,000 rpm for 4 min. The emulsion was stored at 10 °C for 16 h, and air bubbles were removed using an ultrasonic homogenizer at 25 °C and 50% power (450 W) for 10 min.

Particle size analysis

Encapsulation size was determined in suspension and particle size distribution using HORIBA SZ-100 for window (z type) Ver 2.20 with dynamic light scattering method. The particle size distribution was expressed in terms of Polydispersity Index (PI), while particle size was reported as the Z-Average.

Response surface methodology design

A Central Composite Design (CCD) within the Response Surface Methodology (RSM) framework was utilized to structure the experimental design and explore how 3 independent variables influence the process. These variables included pH (4, 5 and 6), the ratio of coating-to-oil (1, 2 and 3 g/g), and operation temperature (50, 55 and 60 °C). The dependent variables studied were the PI and Z-average, which served as responses to changes in the independent variables. To facilitate analysis, the actual values of these variables were converted into coded values, as presented in the corresponding experimental **Table 1**.

Table 1 Experimental ranges and factor levels of the independent process variables.

Independent variable	Pattern code				
	$-\alpha$	-1	0	$+1$	$+\alpha$
pH (X_1)	3.31	4	5	6	6.68
Ratio coating to oil, g/g (X_2)	0.31	1	2	3	3.68
Temperature, °C (X_3)	46.59	50	55	60	63.40

The relationship between the PI, Z-Average, and the independent variables was modeled using a second-order polynomial equation. This equation incorporates linear, quadratic, and interaction terms to predict the response variable (yy), with regression coefficients (β) describing the contribution of each term. Following a second-order polynomial equation as shown in Eq. (1).

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k-1} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \varepsilon. \tag{1}$$

where various x_i and x_j are independent variables, respectively, y is the response variables; β_0, β_i, β_{ii} and β_{ij} are the regression coefficients, and k is the number of variables. In this research, the independent variables were pH (X_1), *the* ratio between coating and oil (X_2), and operating temperature (X_3); Y was responsible for variable dependent, the PI, and Z-Average. The equation Y is shown in Eq. (2).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 \tag{2}$$

Morphological analysis on encapsulates

The morphology of the encapsulates in suspension was observed using a scanning electron microscope (SEM) Jeol JSM 6510 LA. Before the morphological analysis was conducted, the suspension was solidified using freeze drying.

Effectiveness of biopesticides

An efficacy test was conducted to evaluate the effectiveness and capability of citronella oil-based biopesticides in controlling caterpillar pests on mustard greens. The test involved 2 treatments: A control group (0% citronella leaf extract concentration) and a biopesticide group (1.5% citronella leaf extract concentration). The observed parameter in the study was the time to initial mortality of the pests.

Results and discussion
Response surface methodology analysis

The influence of variables on the PI and Z-Average was optimized using RSM with a CCD. The obtained PI values and Z-Average in both observed and predicted responses are presented in **Table 2**, with the corresponding error calculated using Eq. (3).

$$\%error = \frac{|observed - predicted|}{observed} \times 100\% \tag{3}$$

Table 2 The set of experimental variables based on the Central Composite Design (CCD) and the observed responses of the PI and Z-average.

Run	Factor			PI Value			Z-Average Value		
	pH	Ratio coating to oil (g/g)	Temp (°C)	Observed	Predicted	Error (%)	Observed Value (nm)	Predicted Value (nm)	Error (%)
1	4	1	50	0.480	0.727	4.20	1,339.400	1,395.624	51.48
2	4	1	60	0.525	0.645	16.92	1,568.200	1,833.474	22.92
3	4	3	50	1.579	1.497	1.83	4,215.100	4,137.816	5.17
4	4	3	60	0.996	1.156	0.71	4,379.800	4,348.816	16.08
5	6	1	50	0.945	0.938	7.96	1,596.300	1,723.390	0.66
6	6	1	60	0.624	0.859	6.98	2,485.200	2,658.590	37.74
7	6	3	50	1.168	1.201	6.59	2,567.600	2,398.432	2.87
8	6	3	60	0.956	0.862	1.30	3,066.900	3,106.782	9.75
9	3.31	2	55	1.434	1.243	1.72	4,687.900	4,607.445	13.32
10	6.68	2	55	1.201	1.174	1.42	3,894.100	3,838.640	2.22
11	5	0.31	55	0.695	0.414	60.47	535.000	211.502	40.37
12	5	3.62	55	1.002	1.064	6.93	2,706.700	2,894.284	6.28
13	5	2	46.51	1.325	1.284	3.74	2,242.800	2,326.675	3.05
14	5	2	63.40	1.108	0.930	6.26	3,510.300	3,290.511	15.99
15	5	2	55	1.529	1.556	16.48	4,737.400	5,518.010	1.81
16	5	2	55	1.547	1.556	12.07	6,275.300	5,518.010	0.62

The Mean Absolute Percentage Error (MAPE) was employed to evaluate the model's predictive performance [22]. MAPE measures the average percentage deviation between forecasted and observed values, offering an intuitive understanding of the model's accuracy using Eq. (4) [23].

$$MAPE = \frac{1}{n} \sum_{i=1}^{n} \frac{|Observed - Pedicted|}{Observed} \times 100\% \qquad (4)$$

The MAPE values can be classified into 4 categories to assess model performance: Very high accuracy (< 10%), good accuracy (10% - 20%), moderate accuracy (20% - 50%), and low accuracy (> 50%). The MAPE obtained from the optimization, as shown in Eq. (4), was 14.39%. This indicates a relatively high level of accuracy in the experimental results. The low MAPE value suggests minimal deviation from the actual values, thus ensuring the validity and reliability of the data. Moreover, this finding implies that the experimental methodology employed is effective and reliable in generating accurate data [24]. The discrepancy between the empirical and theoretical PI values is visually depicted in **Figure 2**.

This graph visualizes the degree of alignment between the predictive model and observational data. Clearly, it illustrates the extent to which the model can represent patterns and trends observed in the data. RSM involved building a mathematical model, variance analysis, Pareto analysis, and model validation. A second-order polynomial equation was derived from RSM. This equation represents the relationship between the independent variables (X) and the dependent

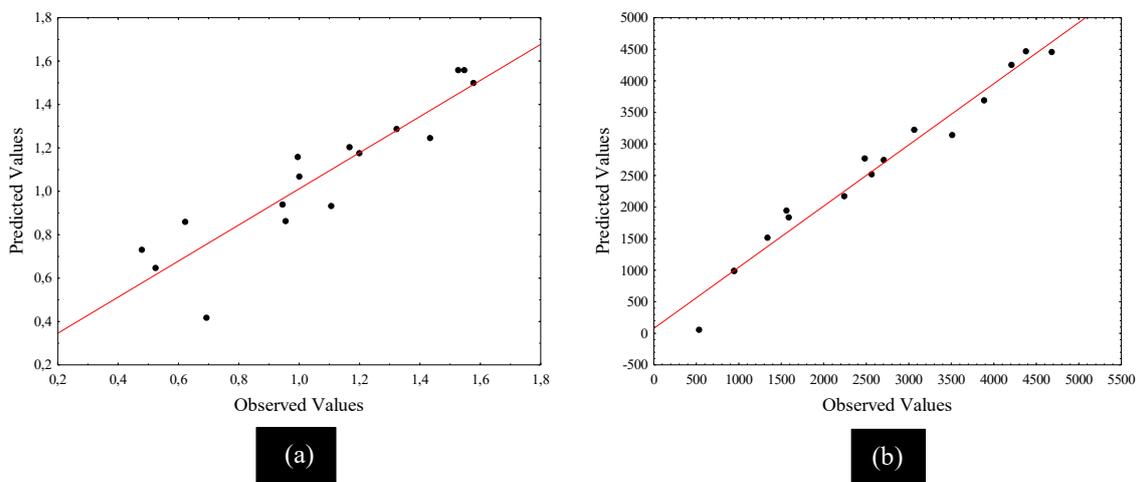variable (Y), enabling predictions and optimization of the system's performance.

Figure 2 Graphical comparison of observed and predicted responses (a) PI value (b) Z-average.

Based on **Figure 2**, the comparison between observed and predicted response values can be observed. Black dots represent the observed responses, while a red line indicates the predicted responses. The figure shows that the observed response values closely align with the predicted values, indicating high accuracy and minimal errors in the experiment. A polynomial mathematical model was developed to analyze the variables' influence on the PI and Z-average value, expressed in the following equation.

$$Y_{PI} = 1.556X_0 + 0.193X_2 - 0.105X_3 - 0.126\ X_1X_2 - 0.064X_2X_3 - 0.123X_1^2 - 0.288X_2^2 - 0.158X_3^2 \quad (5)$$

$$Y_{Z\text{-Average}} = 5518.01 + 797.6X_2 - 516.79X_1X_2 - 457.84X_1^2 - 1401.88X_2^2 - 957.92X_3^2 \quad (6)$$

Conversely, RSM also provides an Analysis of Variance (ANOVA), which can help identify significant factors, build predictive models, and ensure the reliability of optimization results. In **Table 3**, it can be seen that this study has an accuracy level of 0.832. In other words, 83.21% of the research data aligns with the values predicted by the model.

Table 3 ANOVA test result on PI value.

Factor	Sum square	Df	Mean square	*p* value
X_1	0.005694	1	0.005694	0.1063
X_1^2	0.140219	1	0.140219	0.0216
X_2	0.510844	1	0.510844	0.0113
X_2^2	0.772912	1	0.772912	0.0092
X_3	0.150983	1	0.150983	0.0208
X_3^2	0.233429	1	0.233429	0.0167
$X_1.X_2$	0.128778	1	0.128778	0.0225
$X_1.X_3$	0.000003	1	0.000003	0.9121
$X_2.X_3$	0.033670	1	0.033670	0.0440

Factor	Sum square	Df	Mean square	*p* value
Lack of fit	0.326700	5	0.065340	0.0377
error	0.000162	1	0.000162	
Total SS	1.946406	15		
R^2	0.8321		Adj R^2	0.580170

The *p*-value results indicate that the model's prediction parameters are statistically significant when $p < 0.05$, meaning they have a meaningful influence on the response variable. Conversely, parameters with $p > 0.05$ are not considered significant. The analysis of variance (ANOVA) for the PI value model, shown in **Table 3**, reveals a lack of fit *p*-value of 0.0377 - below the 0.05 threshold - indicating a statistically significant difference between the model and the observed data. This suggests the model may not fully account for all variability in the response, possibly due to unmodeled interactions or higher-order effects. Ideally, a non-significant lack of fit ($p > 0.05$) is preferred, as it suggests the model accurately represents the data, with remaining error attributed to random variation. Despite this, the model still demonstrates a relatively strong fit, with a coefficient of determination (R^2) of 0.8321. Notably, the lack of fit value in **Table 3** is 0.038, reinforcing the conclusion that the current second-order linear model may be insufficient to capture the full complexity of the system. Meanwhile, the ANOVA for the effect of variables on the Z-average value is presented in **Table 4**.
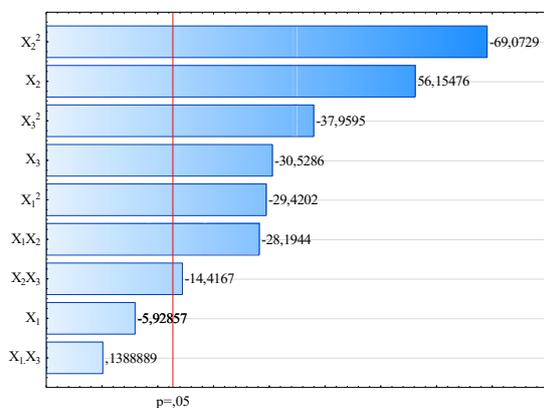
Table 4 ANOVA test result on Z-average value.

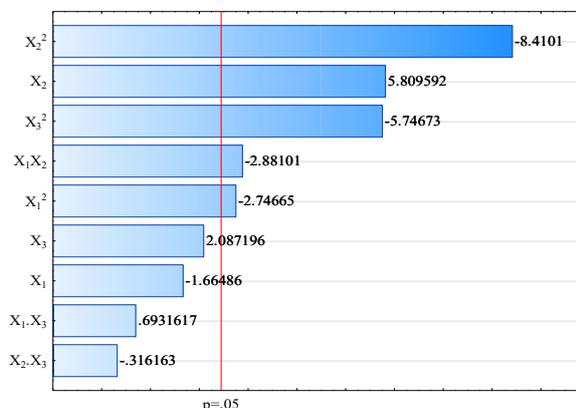| Factor	Sum Square	Df	Mean Square	*p* value
X_1	713474	1	713474	0.146996
X_1^2	1941925	1	1941925	0.033440
X_2	8687931	1	8687931	0.001142
X_2^2	18206522	1	18206522	0.000154
X_3	1121377	1	1121377	0.081915
X_3^2	8500935	1	8500935	0.001208
$X_1 . X_2$	2136555	1	2136555	0.028021
$X_1 . X_3$	123679	1	123679	0.514131
$X_2 . X_3$	25730	1	25730	0.762588
error	1544459	6	257410	
Total SS	34801072	15		
R^2	0.95562	Adj R^2	0.88905	

The significance of each independent variable on the Z-Average value was evaluated using ANOVA, where a *p*-value less than 0.05 indicates a statistically significant effect. **Table 4** presents the impact of pH (X1), the coating-to-oil ratio (X2), and temperature (X3). Among these, the coating-to-oil ratio was found to have the most significant effect on the Z-Average value, while pH and temperature showed less pronounced impacts. Additionally, the ANOVA results indicate that all 3 factors - pH, coating-to-oil ratio, and encapsulation temperature - contribute significantly to the variation in the response variable. The model demonstrates a high

level of accuracy, with an R^2 value of 0.956, meaning it accounts for approximately 95.562% of the total variability. The remaining 4.438% is likely due to uncontrolled variables not included in the model, such as stirring speed or ultrasonic processing parameters. **Figure 3** presents a Pareto Chart highlighting the most and least influential parameters.

Figure 3 Pareto diagram of effect variables (a) PI value (b) Z-average value.

Figure 3(a) illustrates the effect of variables on the PI value, where the quadratic ratio of coating to oil (X_2^2) has the most significant impact, at -69.073. This negative value indicates that a reduction in X_2^2 will lead to decreased encapsulation stability. Conversely, the linear ratio of coating to oil (X_2) has a significant effect of $+56.154$, meaning that an increase in X_2 will enhance encapsulation stability. Based on this explanation, the coating-to-oil ratio is crucial for encapsulation stability, as excessive coating can cause thickening, particle aggregation, and reduced efficiency [25]. This phenomenon will increase the PI value due to reduced homogeneity of the microcapsules [26]. Conversely, the oil coating will be imperfect if the ratio is too low, reducing the encapsulant's performance. Lower performance of encapsulant indicates a suboptimal capacity of the encapsulant to maintain the stability of the citronella oil [27,28]. Additionally, the quadratic process temperature and linear process temperature (X_3^2 and X_3) also affect the PI value. In this study, X_3^2 has a value of -37.959, and X_3 has a value of -30.529. These negative values indicate that an increase in temperature will reduce encapsulation stability. This is because the viscosity of the coating material will decrease, making the coating too runny [29,30]. This condition reduces encapsulation efficiency by preventing the formation of a strong coating [31]. On the other hand, the pH in this study has a value of -29.420, indicating that a reduction in pH will affect encapsulation quality [32]. his phenomenon is caused by electrostatic interactions between the coating material and essential oil, which depend on pH. In highly acidic conditions, the coating loses its charge, and proteins such as those in gum arabic degrade, reducing their ability to form stable microcapsules. [33,34].

In **Figure 3(b)**, the Z-Average Pareto chart shows that the quadratic ratio coating to oil (X_3^2) has the most substantial negative impact, -8.4101, indicating that increasing the ratio reduces particle size. More carriers dilute the system, preventing more extensive particle formation and increasing the Z-average. [35]. In addition to the X_3^2, the quadratic variable of temperature (X_2^2) also has a negative impact on particle size distribution, with a value of -5.745. This suggests that at certain temperatures, changes in conditions will lead to a decrease in particle size. Higher temperatures can accelerate solvent evaporation during encapsulation, resulting in smaller particles [36]. However, if the operating temperature is too high, the viscosity of the suspension will decrease, which can lead to the brittleness of the protective matrix. The viscosity of the matrix plays a crucial role in how well it wets and bonds to these elements. Lower viscosity can hinder proper wetting and lead to weaker interfacial adhesion. A weak

interface allows cracks to initiate and propagate more easily through the material, contributing to brittle behaviour [37,38]. The research also examined the

effects of temperature, the coating-to-oil ratio, and pH on the PI of citronella oil-based biopesticides and the optimum process conditions, as illustrated in **Figure 4**.
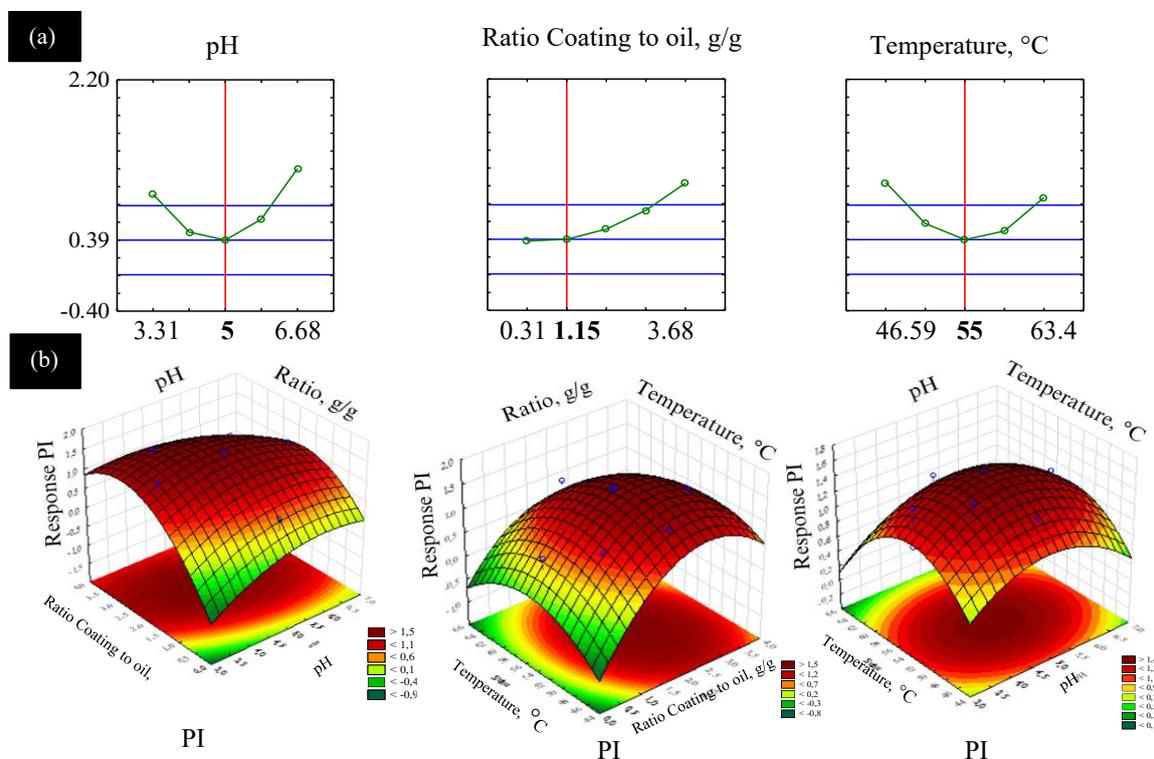

Figure 4 (a) Optimum process condition based on CCD (b) Response surface plot of each parameter PI.

The study shows that several parameters, such as temperature, the ratio between the coating material and citronella oil, and pH, affect the PI, which describes the distribution and uniformity of particle sizes. As shown on the y-axis of **Figure 4(a)**, PI values range from 0 to 1, where lower values indicate a more uniform and stable particle size distribution. Therefore, lower PI values are more favourable. A stable PI value falls within the range of 0 - 1 [39]. The analysis results from **Figure 3(a)**, indicate that the ratio between the coating material and essential oil is the most influential parameter on PI, with an optimal coating-to-oil ratio of 1.15:1, which is reflected in **Figure 4(a)**. The quadratic

ratio also shows significant influence with a *p*-value of 0.009. The optimal conditions for achieving the best PI value are shown in **Figure 4(a)**. The figure indicates that the optimal encapsulation conditions for citronella oil-based biopesticides are achieved at a pH of 5, a coating-to-oil ratio of 1:1.59 g/g, and a temperature of 55 °C. Under these conditions, the process yields an encapsulation diameter of 413.75 nm. On the other hand, the optimum process condition obtained and effects of temperature, the ratio of coating to citronella oil, and pH on the Z-Average of citronella oil-based biopesticides were also maintained, as illustrated in **Figure 5**.
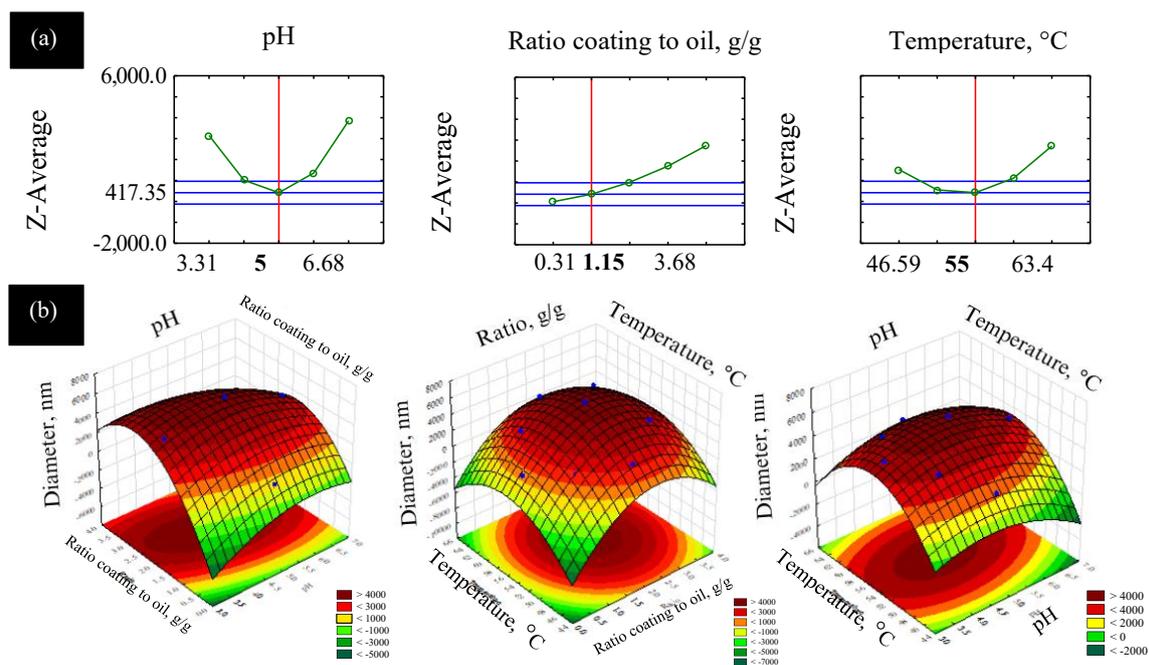
Figure 5 (a) Optimum process condition based on CCD (b) Response surface plot of each parameter on Z-Average.

The optimum process conditions shown in **Figure 5(a)** highlight that the optimal encapsulation conditions for citronella oil-based biopesticides are achieved at a pH of 5, a coating-to-oil ratio coating to oil of 1:1.591 g/g, and a temperature of 55 °C. Under these conditions, the resulting encapsulation diameter is 413.75 nm. The interplay of ratio coating to oil, pH, and temperature influences the encapsulation diameter. An increase in the ratio of coating to oil leads to a larger encapsulation diameter, due to the availability of more wall material, which forms thicker encapsulation layers [40]. In contrast, higher pH values may reduce electrostatic repulsion or viscosity, resulting in smaller particle sizes [41]. Elevated temperatures increase molecular mobility, which can promote the formation of larger particles [41]. Furthermore, it is important to note that the encapsulation diameter remains below 1,000 nm when the temperature is maintained under 47 °C and the coating-to-oil ratio is kept below 2. This condition is essential to ensure the formulation remains within the nanometer scale, which is beneficial for enhancing the stability and bioactivity of the biopesticide.

Microscopic analysis

The final results of the samples obtained can be seen in **Figure 6(a)**, while the microscopic test result can be seen in **Figure 6(b)** The microscopic structure of the encapsulated powder was observed using the SEM method. Prior to this, the biopesticide solution with the central point formulation was spray-dried using the Freeze-drying method. From **Figure 6(b)**, it can be seen the microscopic observation at 5,000× and 1,000× magnification. The results of the SEM analysis in **Figure 6(b)** show a cross-section of the obtained sample. The image shows that the sample formed is a solid particle that has holes or pores shown in black.

Optimal particle size balances maximizing shelf life and preserving the oil's efficacy, while ensuring the size is not so small as to risk premature release of the citronella oil. Larger particles have the potential to store a more significant amount of essential oil. In comparison, smaller particles may accelerate the release of the oil into the environment [42]. The combination of different particle sizes contributes to a gradual release mechanism, which is ideal for enhancing the duration of biopesticide effectiveness in field applications [43]. The rough surface texture increases the surface area of the particles, allowing better interaction with external media and facilitating a controlled release of the oil as needed.
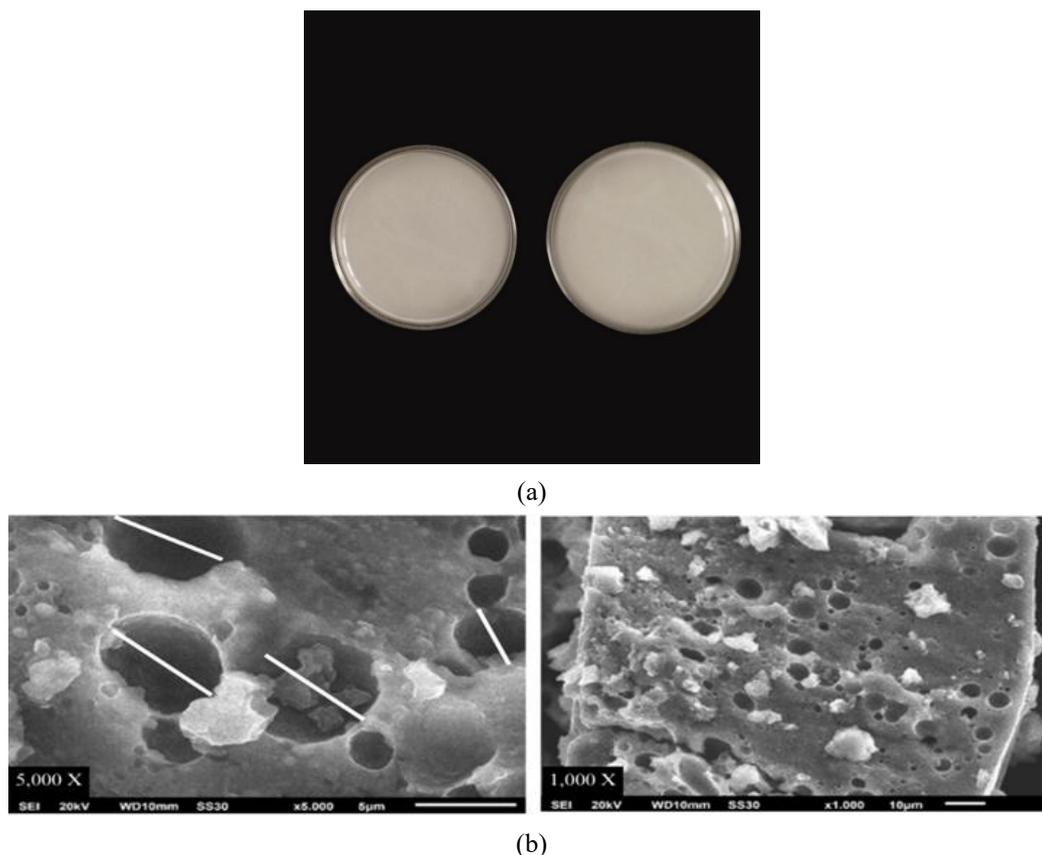
(a)

(b)

Figure 6 (a) Final product (b) Macroscopic analysis of encapsulation biopesticides.

Effectiveness concentration of citronella oil as biopesticide

The effectiveness of the citronella oil-based biopesticide was tested on 7 cabbage caterpillars (*Spodoptera litura*). The biopesticide was applied to the caterpillars every 8 h for 7 days, with 3 sprays per day. The results are shown in **Figure 7**. As shown in **Figure 7**, With 9 caterpillars in each group, the data indicates a contrasting mortality pattern between the control (only citronella oil applied) and the encapsulated biopesticide treatments.

The number of caterpillars used in the research was constrained by the design and scope of the laboratory procedure. The experimental setup allowed for only a limited number of individuals to be observed within the available timeframe and resources. While this controlled environment ensured consistency and reduced external variability. Despite these constraints, the results offer valuable initial insights and lay the groundwork for future studies involving larger and more diverse samples under similar or natural conditions.

The control group exhibited a more rapid or 'burst-like' effect, with most of the caterpillars succumbing between day 2 and day 4, reaching 100% mortality by day 4. In contrast, the encapsulated biopesticide demonstrated a more gradual and seemingly stagnant effect after the initial days. While it induced mortality earlier than the control, reaching 78% mortality by day 3, the rate of death slowed considerably, only reaching 100% mortality by the end of the 7-day observation period. These findings suggest that while the encapsulated biopesticide initiated mortality more quickly than the control, its overall effect was more gradual and sustained over time. In contrast, the control group exhibited a sharp, short-term increase in mortality. This indicates that the encapsulated formulation may offer a slower-release mechanism, potentially extending its efficacy over a longer period, which could have practical implications for pest management strategies requiring prolonged action.
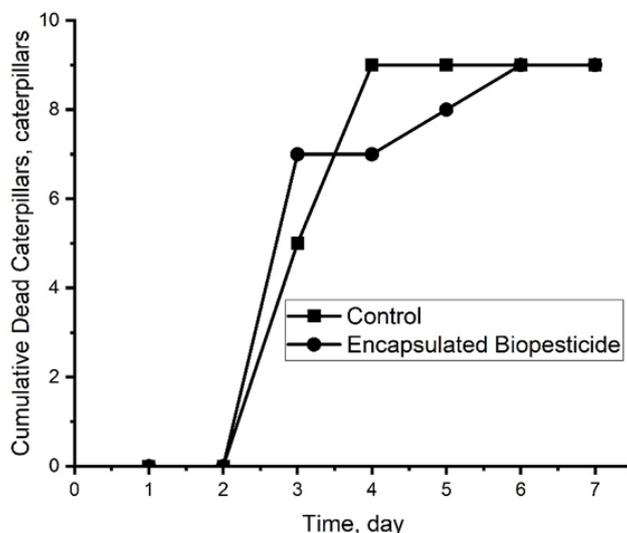
Figure 7 Effectiveness of biopesticide.

Conclusions

Biopesticide encapsulated from citronella oil with gum arabic via coacervation method has been successfully created. The optimal encapsulation conditions calculated by RSM for citronella oil-based biopesticides were determined at a pH of 5, a coating-to-oil ratio of 1:1.591 g/g, and a temperature of 55 °C, resulting in an encapsulation diameter of 413.75 nm and a PI of 0.39. The biopesticide effectively controlled *Spodoptera litura*, achieving 100% mortality within 7 days. Mortality increased gradually, with significant effects observed from day 2 to day 4 as the active compounds disrupted the caterpillars' physiological systems. These results confirm the potential of citronella oil-based biopesticides as an effective alternative for pest control.

Declaration of Generative AI in Scientific Writing

The authors recognize that generative AI tools (such as QuillBot and OpenAI's ChatGPT) were utilized during the preparation of this manuscript, solely to assist with language refinement and grammar editing. No sections of the content were generated, nor was any data interpreted, by AI. The authors assume complete responsibility for the work's content and the conclusions drawn.

Credit Author Statement

Prima Astuti Handayani Conceptualization, Methodology, Supervision, Funding acquisition, and Writing –original draft

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