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The Efficacy Of Encapsulated Castor (*Ricinus communis*) Leaf Extract Against *Colletotrichum* Sp. Causing Antracnose In Curly Red Chili

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Abstract

Penyakit antraknosa pada cabai merah keriting dapat dikendalikan dengan pestisida nabati ekstrak tanaman, namun formulasi nya yang cair mudah terdegradasi sehingga menurunkan efektivitas pengendalian. Penelitian ini mengevaluasi efikasi dari ekstrak daun jarak kepyar yang di enkapsulasi dalam mengendalikan *Colletotrichum* sp. pada Cabai merah keriting. Penelitian dilaksanakan pada bulan Februari sampai Juli 2025 di Laboratorium Proteksi Tanaman, Fakultas Pertanian, UPN "Veteran" Yogyakarta dan untuk proses enkapsulasi dilakukan di Pusat Studi Pangan dan Gizi Universitas Gadjah Mada. Metode yang digunakan adalah Rancangan Acak Lengkap secara *in vitro* dan *in vivo* dengan 6 perlakuan. Parameter pengamatan meliputi diameter koloni jamur, persentase daya hambat, kejadian penyakit, keparahan penyakit, area di bawah kurva perkembangan penyakit dan efektifitas pestisida. Data hasil pengamatan dianalisis menggunakan *Analysis of Variance* dan dilanjutkan dengan Uji Kontras Ortogonal pada taraf uji 5%. Hasil uji *in vitro* menunjukkan efektivitas tertinggi pada ekstrak non-enkapsulasi 1%, sedangkan uji *in vivo* menunjukkan bahwa ekstrak daun jarak yang dienkapsulasi tidak berbeda nyata dibandingkan ekstrak non-enkapsulasi. Efikasi ekstrak enkapsulasi 0,5% masih lebih rendah daripada fungisida sintetis Propineb 70%, tetapi tetap menunjukkan potensi besar sebagai alternatif pengendalian antraknosa cabai merah keriting

Kata kunci: *Ricinus communis*, Ekstrak daun jarak kepyar, Enkapsulasi, *Colletotrichum* sp., Cabai merah keriting

Abstract

Anthracnose disease, which attacks curly red chili, can be controlled with botanical plant extract pesticides; however, the liquid formulation is easily degraded, reducing its effectiveness. This study evaluated the efficacy of encapsulated Castor leaf extract against Colletotrichum sp. on curly red chili. The research was conducted from February to July 2025 at the Plant Protection Laboratory, Faculty of Agriculture, UPN "Veteran" Yogyakarta, and the encapsulation process was carried out at Pusat Studi Pangan dan Gizi Universitas Gadjah Mada. The method used was a completely randomized design, both in vitro and in vivo, with six treatments. Observation parameters included fungal colony diameter, percentage of inhibition, disease incidence, disease severity, Area Under the Disease Development Curve, and pesticide effectiveness. Observation data were analyzed using Analysis of Variance and followed by the Orthogonal Contrast Test at 5% significance level. In vitro assays demonstrated the highest effectiveness of the non-encapsulated extract at 1%. In contrast, in vivo evaluations showed that the encapsulated castor leaf extractdid not show a significant difference compared to the non-encapsulated extract in vivo . The efficacy of the 0.5% encapsulated extract was still lower than that of the synthetic fungicide Propineb 70%, yet it demonstrated considerable potential as an alternative for managing anthracnose in curly red chili.

Keywords: *Ricinus communis, Castor leaf extract, Encapsulation, Colletotrichum sp., Curly red chili*

Introduction

Chili has become an important commodity in Indonesia, where its price can affect political and socio-economic conditions. Even the price of chili can be one of the parameters to measure the government's performance in building food security (Wijaya *et al*., 2020). One type of chili that has high economic value is curly red chili, therefore, it is quite widely cultivated by farmers. The distinctive taste and aroma of curly red chili make it a required ingredient in every Indonesian dish (Zain *et al*., 2024). Saida (2023) said that based on the calculation of the Food Balance Sheet (NBM) in the period 2000-2022, chili consumption tends to increase, especially the use of chili for food ingredients, from 696 thousand tons in 2000 to 960 thousand tons in 2022, or an increase of 5.18% per year. The analysis of increased consumption also analyzes that there will be an average increase in national consumption of 1,340 thousand tons (2023-2027). However, the Surplus chili produced is relatively low compared to the average national consumption.

Due to several factors, including crop failures caused by diseases and pests of chili plants, efforts to increase production have not yet been successful. Changes in the pattern of the rainy and dry seasons often result in the emergence of diseases in chili plants, especially curly chili which are quite susceptible to disease. Frequent diseases reduce crop yields and cause losses for farmers (Sholihah *et al*., 2020). Hyder *et al*., (2021) report that chili plants are susceptible to more than 100 types of infection, including fungal infections. Some fungal diseases that attack chili are: *Rhizoctonia* root rot, Damping-

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off, Powdery mildew, *Fusarium* wilt, *Phytophthora* pod rot, *Cercospora* leaf spot, *Phytophthora* blight, and chili anthracnose (Gondal, 2018). *Colletotrichum* spp. is one of the major fungi affecting chili production worldwide. Whereas can cause anthracnose and fruit rot in chili, which significantly affects crop yield and quality. This pathogen can cause infections at pre- and post-harvest stages with yield losses of up to 50% (Silva *et al*., 2019; Chowdhury *et al*., 2023).

Chemical fungicides have historically been the primary choice for controlling diseases caused by *Colletotrichum* spp. However, the continued use of synthetic chemicals in the environment has been shown to have harmful long-term effects (John and Babu, 2021). The need to replace chemicals as pesticides has led to new strategies for finding alternative plant protection agents. Plant-based agents such as essential oils and extracts have come into the spotlight due to their biodegradability, mode of action, and potential for lower pathogen resistance (Arora *et al*., 2022). Botanical pesticides or called natural pesticides, are pesticides derived from plants that can be used to control pests and plant diseases. Plants contain many chemicals, called secondary metabolites. They are used by plants for self-defense against invading organisms. The active ingredients contained in plants function as defense tools, attractants, antifertility, killers, antioxidants, and antimicrobials (Sari and Shofi, 2012).

Indonesia has abundant biodiversity, so it is quite easy to obtain plants that meet the criteria as raw materials for botanical pesticides (Kusumawati and Istiqomah, 2022). One of the local plants that is easily obtained and has the potential to have biopesticide activity is castor (*Ricinus communis* L.). Castor leaf contains secondary metabolite compounds, namely alkaloids, flavonoids, phenolics, and terpenoids which are toxic to microorganisms (Safrina *et al*., 2017). Flavonoid compounds in castor oil have the ability to inhibit bacterial growth with several different mechanisms (Sari and Shofi 2012). The results of a study by Salinas-Sanchez *et al*., (2021) showed that linoleic acid contained in *R. communis* leaf extract can act as an insecticide against *Sipha flava* (yellow sugarcane aphid) in sugarcane plants. Water extracts from seeds, leaves, and even roots of *R. communis* have also been shown to show larvacidal activity against *Plutella xylostella* in corn plants (Kodjo *et al*., 2011).

R. communis is usually applied as a botanical pesticide in the form of a liquid extract. The main issue with biopesticides with a liquid formula, is the product stability. Liquid biopesticides cannot maintain product stability because their active ingredients are easily damaged by environmental conditions. Therefore, one of the innovations that can be developed to maintain the stability of biopesticide products that have a direct impact on the viability of secondary metabolite compounds is the encapsulation process (Azizah and Fitriani, 2015). Encapsulation is the process of coating the core material as an active ingredient with another material as a wall material (Risch, 1995). Encapsulation allows the active ingredient to be released periodically through the encapsulant layer, so this can also increase the efficiency of material use. It can maintain the viability of the active compound so that it is effective during its use (Azizah and Fitriani, 2015).

However, studies evaluating the effectiveness of encapsulated *Ricinus communis* leaf extract against *Colletotrichum* sp. on chili, particularly comparing *in vitro* and *in vivo* responses, remain limited. The objectives of this study were: (1) to evaluate the efficacy of encapsulated and non-encapsulated castor (*Ricinus communis* L.) leaf extracts against *Colletotrichum* sp. causing anthracnose in curly chili; (2) to determine the most effective concentration of the extract in suppressing the pathogen; and (3) to compare the efficacy of the encapsulated extract with that of a synthetic fungicide.

Materials and methods

This research was conducted from February to July 2025 at the Plant Protection Laboratory, Faculty of Agriculture, UPN "Veteran" Yogyakarta, and the encapsulation process was carried out at the Pusat Studi Pangan dan Gizi (Food and Nutrition Study Center), Universitas Gadjah Mada. This research was carried out under a completely randomized design (CRD), which consisted of both *in vitro* (food poisoning) and *in vivo* (wounding inoculation) assays in the laboratory. The *in vitro* test was used on PDA medium with three replicates, while the *in vivo* test was applied to chili fruits with five replicates. There were six treatments, namely: K0 = Without any treatment/control, K1 = non-encapsulated castor leaf extract 0.5%, K2 = non-encapsulated castor leaf extract 1%, K3 = encapsulated castor leaf extract 0.5%, K4 = encapsulated castor leaf extract 1%, and K5 = synthetic chemical fungicide Propineb 70%.

Extraction and encapsulation

Ricinus communis leaves were collected from Grogol Village, Pejawaran, Banjarnegara, Central Java. The leaf were dried in an oven at 45 °C for 48 hours and ground into fine powder (Chan-Chupul *et al.,* 2023). A total of 85 g of leaf powder was macerated in 850 mL of 70% ethanol for 48 hours, filtered, and concentrated using a rotary evaporator at 40 °C to obtain 400 mL extract. Encapsulation was carried out using the ionic gelation method followed by freeze drying (Maluin *et al*., 2019). Chitosan (500

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mg) was dissolved in 100 mL of 1% acetic acid under manual stirring. Separately, 1 mL of *Ricinus communis* extract was mixed with 100 mL of N,N-dimethylformamide (DMF) and combined with the chitosan solution under magnetic stirring until fully dissolved (2 hours). Subsequently, 8 mL of Tween-80 (2% v/v) was added as a stabilizer. A sodium tripolyphosphate (TPP) solution was prepared by dissolving 800 mg of TPP in 40 mL of distilled water, and then adding it to the mixture under magnetic stirring. The resulting suspension was centrifuged at 4,020 rpm for 10 minutes, and the pellet was freeze-dried overnight to obtain the encapsulated extract.

Pathogen isolation

The PDA medium used in this study was prepared from potato, sugar, and agar at a ratio of 200:20:20 (g/L), and contains 1% Chloramphenicol. *Colletotrichum* sp. was isolated from curly red chili fruits exhibiting anthracnose symptoms. Symptomatic tissue surfaces were sterilized with 1% Clorox, air dried, cut between the lesion and healthy tissue interface, and aseptically placed on PDA medium for incubation at room temperature. The fungus that grew was then purified and identified to ensure its conformity with the characteristics of the *Colletotrichum sp.*

In vitro assay

PDA stock was melted using a microwave and equilibrated in a 60 °C water bath to preserve the integrity of the extract's active compounds. Encapsulated extracts were dissolved in distilled water using a mortar, while non-encapsulated extracts and synthetic fungicides were used without prior dissolution. Each treatment solutions were added to the PDA using a micropipette and homogenized with a magnetic stirrer under laminar air flow. The media were poured into Petri dishes (15 mL) and allowed to solidify. *Colletotrichum* sp. inoculum was cut using a cork borer and placed at the center of each plate, followed by incubation at room temperature for 8 days. Colony diameters were measured daily. Each treatment was performed in triplicate. Colony diameter was measured daily, and the data obtained were used to calculate the percentage of inhibition according to the formula described by Al-Reza *et al.*, (2010): Inhibition percentage = $\frac{C-T}{C}$ x 100%. Where, C = the average diameter of colonies in the negative control and T = colony diameter in the treatment.

In vivo assay

An *in vivo* assay was carried out through the wounding inoculation method. The process was performed by disolving all extracts and synthetic fungicides in aquadest according to the required concentrations. Chili fruits were surface-sterilized using tissues moistened with 1% Clorox solution, then air-dried. Each fruit was punctured three times using a sterile dissecting needle, and the wound sites were treated with the respective treatment solutions. *Colletotrichum* sp. isolates were applied to the wounds and allowed to adhere for 24 hours, after which the inoculum was removed. Each treatment was conducted with five replicates. The fruits were then placed on wire screens inside plastic trays (30 × 25 × 3 cm) containing moistened cotton as a humidifier, covered with zip plastic bags, and incubated at room temperature. Observations were conducted for 14 days, with disease incidence and severity recorded every two days. Disease incidence was calculated as the percentage of infected fruits relative to the total number of fruits in each repetition. The percentage of anthracnose disease severity was calculated using a modified formula from Hamidson *et al.*, (2019). Disease severity for each fruit was determined by comparing the lesion size to the fruit size. It was calculated as the average of two ratios: lesion width to fruit circumference and lesion length to fruit length, both expressed as percentages. The resulting value represented the severity percentage per fruit and was then used to calculate overall disease severity using the following formula:

$$DI = \frac{\sum(n \times v)}{N \times V} \times 100\ \%$$

Description :

DI = Disease Severity (%)

n = number of fruits exhibiting a given severity percentage

v = disease severity percentage per fruit (%)

N = Number of fruits observed (4 fruits in one replication)

V = maximum severity value (100%)

The disease severity data were subsequently used to calculate the Area Under the Disease Progress Curve (AUDPC) and efficacy. AUDPC was determined using the formula described by Van der Plank (1963):

$$AUDPC = \sum_{i=1}^{n-1} \frac{y_i + y_{i+1}}{2} \times (t_{i+1} - t_i)$$

Description:

y_i = Assessment of disease severity percentage at the *i*th observation

t_i = Time (in days) at the *i*th observation

n = The total number of observations

Efficacy was calculated using Abbott's formula (Dirjen BSP, 2004): EI = (Ca-Ta) / Ca ×100%. Which, EI = Pesticide efficacy, Ca= Disease Severity in control, Ta= Disease Severity in the treatments. Pesticide efficacy is assessed with the following categories (Elfina *et al.*, 2016): 0= Ineffective, >0-20% = Very low efficacy, >20-40%=

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Low efficacy, >40-60%= Moderate efficacy, >60-80%= High efficacy, and >80%= Very high efficacy.

Data analysis

The observation data were analyzed using Analysis of Variance (ANOVA). When a significant treatment effect was detected, mean separation was performed using the Orthogonal Contrast Test at a 5% significance level with SPSS version 27 software. The contrasts tested included: the control without treatment (K0) vs. all other treatments; the synthetic fungicide Propineb 70% (K5) vs. all extract-based treatments; encapsulated

vs. non-encapsulated extracts (K1 and K2 vs. K3 and K4); between non-encapsulated extracts (K1 vs. K2); and between encapsulated extracts (K3 vs. K4).

Result and Discussion

Inhibition Percentage

The inhibition percentage analysis in **Table 1**. indicated that propineb 70% consistently and significantly suppressed the growth of *Colletotrichum* sp. from 1 to 8 DAI across all measured parameters, confirming the reliability of chemical fungicides as a positive control and benchmark for evaluating castor leaf extracts, both encapsulated and non-encapsulated. Synthetic fungicides remain crucial in the integrated management of anthracnose in chili, as both contact and systemic types effectively reduce disease incidence and severity (Nuraini and Latiffah, 2019). Moreover, *C. capsici* and *C. gloeosporioides* are highly sensitive to propineb, with treatment at 700 ppm capable of inhibiting fungal growth by up to 100% *in vitro* (Astuti *et al*., 2014). In this study, the non-encapsulated extract, particularly at 1%, produced significantly higher inhibition from 2 to 8 DAI, consistent with findings that ethanolic castor leaf extract at the same concentration can suppress 62.7% mycelial growth in food poisoning assays (Chan-Chupul *et al*., 2023). This method is suitable for liquid plant extracts (Deora, 2023). Conversely, the encapsulated extract showed no significant effect due to its lyophilized flake morphology generated by freeze-drying, which hindered solubility and reduced the release of active compounds. This limitation corresponds with the physicochemical properties of chitosan, which is insoluble in water and organic solvents but dissolves in dilute acidic solutions (pH < 6.5) (Pereira *et al*., 2011).

Table 1. Average Inhibition Percentage of *Colletotrichum* sp. Growth by Different Treatments Over Eight Days After Inoculation (DAI)

Treatment	Inhibition Percentage (%)							
	1 DAI	2 DAI	3 DAI	4 DAI	5 DAI	6 DAI	7 DAI	8 DAI
K5 vs.	42.15±0.00	66.98±0.00	73.88±0.00	77.78±0.00	81.13±0.00	83.33±0.00	84.82±0.00	86.00±0.00
K1,K2,K3,K4	28.72±5.60 *	30.47±3.54 *	22.50±7.90 *	19.51±9.20 *	18.52±8.40 *	17.56±7.62 *	15.85±7.87 *	12.96±8.54 *
K1,K2 vs.	30.61±7.14	29.36±5.13	25.22±10.76	22.29±11.97	22.34±10.84	20.88±9.89	18.70±10.37	16.04±10.88
K3,K4	26.83±3.08 ns	30.52±1.14 ns	19.78±1.93 *	16.73±4.93 ns	14.70±1.70 *	14.24±1.86 *	13.01±3.06 *	9.88±4.42 *
K1 vs.	28.72±9.18	26.69±2.23	15.89±1.94	11.77±1.50	12.96±0.70	12.50±1.07	9.71±1.41	6.42±1.84
K2	32.51±5.69 ns	34.16±4.35 *	34.55±4.99 *	32.80±4.90 *	31.72±5.42 *	29.27±5.70 *	27.69±4.92 *	25.67±3.79 *
K3 vs.	24.60±2.05 ns	30.42±1.77 ns	18.38±1.23 ns	17.46±7.60 ns	14.31±1.08 ns	13.00±1.91 ns	12.96±4.56 ns	9.67±6.86 ns
K4	29.06±2.15	30.62±0.34	21.18±1.40	16.01±1.21	15.09±2.36	15.48±0.60	13.05±1.63	10.08±1.28

Note: Values are presented as mean ± SD (n = 6). (*) Indicates significant differences at the 5% level according to orthogonal contrast tests, whereas (ns) denotes non-significant differences. Data were transformed using arcsine $\sqrt{x}$.
K1: non-encapsulated Castor leaf extract 0,5%
K2: non-encapsulated Castor leaf extract 1%
K3: encapsulated Castor leaf extract 0,5%
K4: encapsulated Castor leaf extract 1%
K5: Synthetic chemical fungicide Propineb 70%

Disease incidence

Table 2. showed that treatment with 70% propineb fungicide resulted in the lowest incidence, with a mean value of only 20% at 12 DAI, showing a statistically significant difference from other treatments. Encapsulated extracts exhibited a significant difference compared with non-encapsulated extracts at 6 DAI (25%), although this effect was not sustained in subsequent observations. Landi *et al.* (2021) reported that postharvest application of 0.5% *Ruta graveolens* (rue) essential oil combined with chitosan on papaya fruit effectively reduced disease incidence and severity by 37% and 44%, respectively, compared to the control. This effect was attributed to chitosan-based composite coatings incorporating essential oils (EOs), which can retain the volatile compounds of rue oil and allow their gradual release.

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Table 2. Average Percentage of Anthracnose disease incidence on Curly Red Chili Fruits under Different Treatments

Treatment	Incidence (%)				
	4 DAI	6 DAI	8 DAI	10 DAI	12 DAI
K0 vs. K1,K2,K3,K4,K5	0.00±0.00 4.00±11.81 ns	50.00±17.68 32.00±25.54 ns	95.00±11.18 52.00±30.55 *	95.00±11.18 58.00±29.51 *	95.00±11.18 58.00±29.51 *
K1,K2,K3,K4 vs. K5	5.00±13.08 0.00±0.00 ns	37.50±25.00 10.00±13.69 *	60.00±27.39 20.00±20.92 *	67.50±23.08 20.00±20.92 *	67.50±23.08 20.00±20.92 *
K1,K2 vs. K3,K4	7.50±16.87 2.50±7.91 ns	50.00±23.57 25.00±20.41 *	67.50±31.29 52.50±21.89 ns	72.50±29.93 62.50±13.18 ns	72.50±29.93 62.50±13.18 ns
K1 vs. K2	10.00±22.36 5.00±11.18 ns	50.00±30.62 50.00±17.68 ns	60.00±33.54 75.00±30.62 ns	65.00±37.91 80.00±20.92 ns	65.00±37.91 80.00±20.92 ns
K3 vs. K4	5.00±11.18 ns 0.00±0.00	15.00±22.36 ns 35.00±13.69	40.00±22.36 ns 65.00±13.69	60.00±13.69 ns 65.00±13.69	60.00±13.69 ns 65.00±13.69

Note: Values are presented as mean ± SD (n = 6). (*) Indicates significant differences at the 5% level according to orthogonal contrast tests, whereas (ns) denotes non-significant differences. Data were transformed using arcsine $\sqrt{x}$.
K0: without any treatment
K1: non-encapsulated Castor leaf extract 0,5%
K2: non-encapsulated Castor leaf extract 1%
K3: encapsulated Castor leaf extract 0,5%
K4: encapsulated Castor leaf extract 1%
K5: Synthetic chemical fungicide Propineb 70%

Disease severity

Table 3. Average Percentage of Anthracnose disease Severity on Curly Red Chili under Different Treatment

Treatment	Disease Severity (%)				
	4 DAI	6 DAI	4 DAI	10 DAI	4 DAI
K0 vs. K1,K2,K3,K4,K5	0.00±0.00 0.69±1.84 ns	K0 vs. K1,K2,K3,K4,K5	0.00±0.00 0.69±1.84 ns	K0 vs. K1,K2,K3,K4,K5	0.00±0.00 0.69±1.84 ns
K1,K2,K3,K4 vs. K5	0.87±2.02 0.00±0.00 ns	K1,K2,K3,K4 vs. K5	0.87±2.02 0.00±0.00 ns	K1,K2,K3,K4 vs. K5	0.87±2.02 0.00±0.00 ns
K1,K2 vs. K3,K4	1.01±2.46 0.73±1.60 ns	K1,K2 vs. K3,K4	1.01±2.46 0.73±1.60 ns	K1,K2 vs. K3,K4	1.01±2.46 0.73±1.60 ns
K1 vs. K2	1.53±3.42 0.49±1.09 ns	K1 vs. K2	1.53±3.42 0.49±1.09 ns	K1 vs. K2	1.53±3.42 0.49±1.09 ns
K3 vs. K4	0.52±1.17 ns 0.93±2.08	K3 vs. K4	0.52±1.17 ns 0.93±2.08	K3 vs. K4	0.52±1.17 ns 0.93±2.08

Note: Values are presented as mean ± SD (n=6). (*) Indicates significant differences at the 5% level according to orthogonal contrast tests, whereas (ns) denotes non-significant differences.
K0: without any treatment
K1: non-encapsulated Castor leaf extract 0,5%
K2: non-encapsulated Castor leaf extract 1%
K3: encapsulated Castor leaf extract 0,5%
K4: encapsulated Castor leaf extract 1%
K5: Synthetic chemical fungicide Propineb 70%

Propineb treatment again demonstrated the highest efficacy in **Table 3.**, with a mean severity of only 7.16% at 12 DAI. Encapsulated extracts showed significant differences from non-encapsulated extracts between 6 and 10 DAI, while the 0.5% encapsulated treatment displayed significance at 8 DAI but not thereafter. Overall, the negative control consistently exhibited the highest percentages of both disease incidence and disease severity across all observation periods. Gumede *et al.*, (2025) demonstrated that postharvest application of nanostructured chitosan–thyme oil on tomato fruit inoculated with *Colletotrichum gloeosporioides* reduced disease incidence by 50% relative to the control. Moreover, this treatment achieved a decay severity score of 1, whereas the control reached a score of 4. This result shows that the nanostructured chitosan–thyme oil can slow down pathogen infections, thereby helping to extend the shelf life of produce. The effectiveness in suppressing

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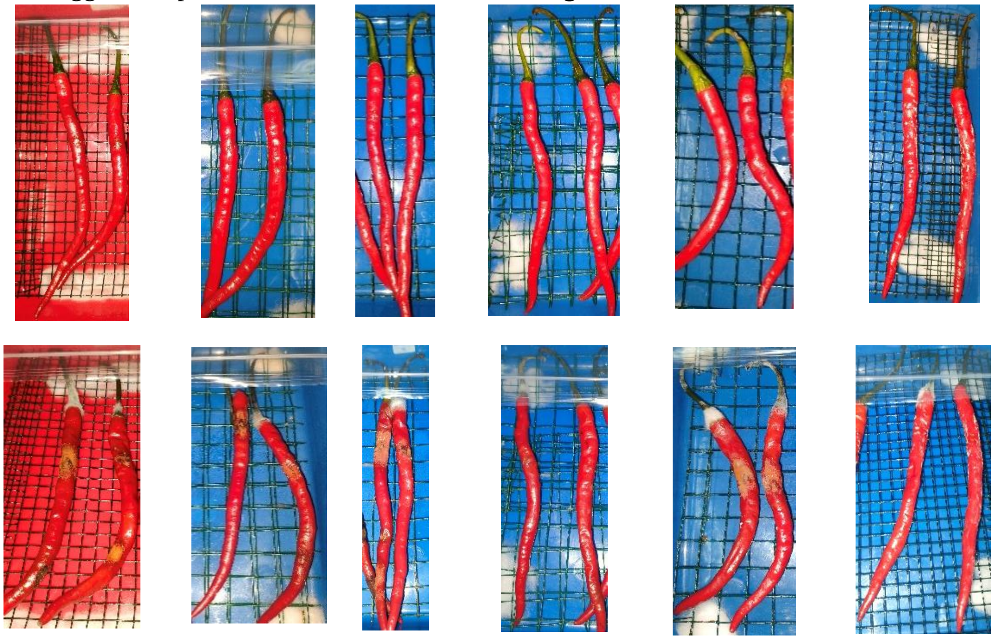
pathogenic fungi in fruit is suggested to result from both direct inhibition of fungal cells and indirect stimulation of fruit defence mechanisms, including their ability to trigger the production of defence-related enzymes. The differences of Letio, as shown, indicate the infection of *Colletotrichum* sp. inoculation across all treatments, as illustrated in **Figure 1**.

3 DAI

12 DAI



K0 **K1** **K2** **K3** **K4** **K5**

Figure 1. Visual comparison of five treatments showing differences at 3 and 12 days after inoculation (DAI).

Area Under the Disease Progress Curve

Table 4. The average Area Under Disease Progress Curve (AUDPC) value of Anthracnose Disease on Curly Red Chili Fruits under Different Treatments

Treatment	AUDPC
K0 vs.	210.63±14.24
K1,K2,K3,K4,K5	92.80±62.55 *
K1,K2,K3,K4 vs.	108.14±60.00 *
K5	31.44±22.10
K1,K2 vs.	137.92±67.00
K3,K4	78.37±33.78 ns
K1 vs.	129.76±74.79
K2	146.07±65.88 ns
K3 vs.	59.75±37.52 ns
K4	96.99±17.10

Note: Values are presented as mean ± SD (n=6). (*) Indicates significant differences at the 5% level according to orthogonal contrast tests, whereas (ns) denotes non-significant differences. Data were transformed using Log (x+1).
K0: without any treatment
K1: non-encapsulated Castor leaf extract 0,5%
K2: non-encapsulated Castor leaf extract 1%
K3: encapsulated Castor leaf extract 0,5%
K4: encapsulated Castor leaf extract 1%
K5: Synthetic chemical fungicide Propineb 70%

Table 4. Area Under the Disease Progress Curve (AUDPC). Significant differences were observed in the negative control treatment, which recorded the highest value of 210.63, and in the positive control treatment, with a value of 31.44. No significant differences were detected among the extract treatments. However, the 0.5% encapsulated extract (59.75) was more effective than any other extract treatment. Although not always statistically significant, the lower AUDPC of the 0.5% encapsulated extract indicates a positive trend in the effectiveness of encapsulation as an alternative control. This is consistent with Rahman *et al.*, (2009), who demonstrated that the combined treatment of *Burkholderia cepacia* B23 with calcium chloride and chitosan effectively suppressed anthracnose development in papaya during storage, yielding the

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lowest AUDPC value (0.0), comparable to the synthetic fungicide benomyl 50% WP as a positive control, and significantly lower (P<0.05) than the water-treated control fruit, which recorded an AUDPC of 32.96. Chitosan as an exogenous substance, enhances the biocontrol efficacy of antagonistic agents (including leaf extracts) against fungal pathogens through the formation of a semi-permeable film that suppresses pathogen development.

Table 5. Average efficacy percentage of treatments in suppressing anthracnose disease development on chili fruits at 4 – 12 days after inoculation

Treatment	Efficacy (%)			
	6 DAI	**8 DAI**	**10 DAI**	**12 DAI**
K1	33.61	41.52	41.34	37.66
K2	27.92	32.89	31.74	28.71
K3	83.83	80.16	69.62	56.69
K4	60.37	55.17	55.63	49.45
K5	85.54	88.14	83.84	82.08

Note: A higher percentage indicates a higher efficacy. DAI: days after inoculation.
K1: non-encapsulated Castor leaf extract 0,5%
K2: non-encapsulated Castor leaf extract 1%
K3: encapsulated Castor leaf extract 0,5%
K4: encapsulated Castor leaf extract 1%
K5: Synthetic chemical fungicide Propineb 70%

Efficacy

As shown in Table 5, the Propineb 70% treatment in this study consistently achieved efficacy above 80%, which was classified as very high efficacy (Elfina *et al*., 2016). In contrast, the non-encapsulated 1% castor leaf extract showed the lowest efficacy, falling into the low efficacy category (20–40%). The 0.5% encapsulated extract reached very high efficacy levels at 6 and 8 DAI (83.83% and 80.17%). High efficacy values indicated the extract's potential to suppress infection and disease severity, supporting its role as a disease control agent. Encapsulation further enhances stability, preserves bioactivity, protects compounds from adverse conditions, and enables controlled release (Zabot *et al*., 2022). Wu *et al*., (2023) revealed that the formulation of chitosan/O-carboxymethyl chitosan/tebuconazole nanoparticles exhibited superior antifungal activity, foliar adhesion, and microbial target adhesion compared with the commercial tebuconazole suspension concentrate. In this research, Chitosan-based nanopesticides act as a "sugar-coated bomb," as *C. gloeosporioides* recognizes chitosan as a nutrient, degrades it, and consequently releases the active ingredient directly at the infection site. These nanoparticles enable precise pesticide delivery, reducing application rates, and minimizing environmental pollution, thereby supporting agricultural sustainability.

Conclusions

Propineb 70% consistently exhibited the highest efficacy across all evaluated parameters, outperforming both encapsulated and non-encapsulated castor leaf extracts. Encapsulation did not significantly enhance antifungal activity *in vitro*, however, it contributed to a reduction in disease severity at 6, 8, and 10 days after inoculation *in vivo*. In the non-encapsulated treatment, the 1% concentration showed significantly higher inhibition *in vitro* compared with the 0.5% concentration, while no significant differences between concentrations were observed *in vivo*. Among encapsulated formulations, the 0.5% concentration did not show significant differences in antifungal activity in either *in vitro* or *in vivo* assays.

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