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ORIGINAL RESEARCH ARTICLE

Antifungal Potential of Different Weed Leachates for the Postharvest Control of Papaya Anthracnose Caused by *Colletotrichum* spp.

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ABSTRACT

A wide variety of fungal pathogens cause postharvest diseases in papaya. Among these, anthracnose caused by *Colletotrichum* spp. is considered one of the most destructive diseases, resulting in significant postharvest losses worldwide. Several plant extracts and leachates have been reported to possess antifungal activity against various fungal pathogens. This study evaluated the efficacy of *Solanum torvum, Amaranthus viridis*, and *Lantana camara* leachates in controlling anthracnose in 'Solo' papaya. Both in vitro and in vivo experiments were arranged using a Completely Randomized Design (CRD). The in vitro test consisted of 11 treatments with 132 samples, while the in vivo test included six treatments with 54 samples. Results showed that all leachates at 5% concentration inhibited the mycelial growth of *Colletotrichum* spp. under in vitro conditions. In vivo, *A. viridis* recorded the lowest disease severity (47.08%), followed by *S. torvum* (65.37%) and *L. camara* (73.06%). Significant differences among treatments were observed for disease severity, visual quality, and degree of shriveling at 3, 5, and 7 days after treatment ($p < 0.05$). The findings suggest that *A. viridis* leachate has promising potential as a natural alternative for the postharvest management of papaya anthracnose by reducing disease development and maintaining postharvest fruit quality. Further studies are recommended to identify the active antifungal compounds, determine their mode of action, and evaluate the effectiveness of the leachates using larger sample sizes under semi-commercial and commercial postharvest storage conditions.

Keywords: *Antifungal activity, botanicals, fruit shelf-life, leachates, poison food technique*

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INTRODUCTION

Papaya (*Carica papaya* L.) is considered one of the most important fruit crops in tropical and subtropical regions because of its desirable taste, high nutritional value, and medicinal properties (Koul et al., 2022). In the Philippines, papaya is also regarded as an economically important fruit crop due to its high market demand and production potential (Tayag, 2026). According to the Philippine Statistics Authority (2026), papaya production in the country reached approximately 2,851.8 metric tons in 2025, highlighting its contribution to the Philippine fruit industry and local economy. However, despite its importance, papaya is highly susceptible to diseases caused by various microorganisms, particularly fungi. This susceptibility is largely attributed to the fruit's thin skin, high moisture content, and rich nutrient composition, which provide favorable conditions for pathogen development (Mudiyansel et al., 2019). Kumar et al. (2021) also reported that papaya is one of the fruits most vulnerable to phytopathogen attack from the preharvest to postharvest stages.

Among the major postharvest diseases affecting papaya, anthracnose caused by *Colletotrichum gloeosporioides* is considered one of the most destructive worldwide. Postharvest losses in papaya have been reported to range from approximately 40% to 100% in developing countries (Tan and Siddiqui, 2022). According to Rampersad (2011), anthracnose is a major limiting factor in papaya production globally. Similarly, Valenzuela et al. (2015) described it as one of the most widespread and devastating diseases of papaya, causing significant losses during the postharvest phase. Anthracnose infections are usually initiated in the field during the early stages of fruit development; however, the pathogen remains quiescent and symptoms become evident only when the fruit reaches the climacteric stage (Sivakumar et al., 2021).

The application of synthetic fungicides remains one of the most widely used approaches for controlling anthracnose caused by *Colletotrichum* spp.; however, concerns regarding fungicide resistance, environmental impact, and food safety have encouraged the search for safer alternatives (Law et al., 2025). Several plant extracts and leachates have been reported to exhibit antifungal activity against a wide range of fungal pathogens (Oveanu et al., 2013; Mehta, 2020). Plant-based products are considered advantageous over synthetic fungicides because they are biodegradable, renewable, locally available, and potentially economical for practical use,

especially among small-scale farmers (Zaker, 2016). The identification and utilization of antifungal compounds from plants therefore represent a promising alternative strategy for reducing fungal deterioration and minimizing postharvest losses.

Several weed species have shown potential as sources of natural antifungal compounds due to the presence of bioactive secondary metabolites such as phenolics, flavonoids, alkaloids, and tannins. *Solanum torvum,* a medicinal plant widely distributed in tropical regions, has been reported to exhibit broad-spectrum antifungal activity against several plant pathogenic fungi and storage molds, indicating its potential as a source of eco-friendly antifungal agents (Irdani et al., 2025). Likewise, *Amaranthus viridis* contains phenolic and antioxidant compounds with reported antimicrobial properties against selected bacterial and fungal pathogens (Sarker et al., 2022). In addition, L*antana camara* extracts have demonstrated inhibitory effects against *Colletotrichum* species by suppressing mycelial growth and conidial development (Mudiyansel et al., 2019).

Despite these reported bioactivities, limited information is available regarding the comparative efficacy of these locally available weed leachates for the postharvest management of papaya anthracnose caused by *Colletotrichum gloeosporioides,* particularly under both in vitro and in vivo conditions. Moreover, most previous studies focused primarily on crude plant extracts or field pathogens, with limited attention given to the utilization of weed leachates as affordable and sustainable postharvest treatments. Therefore, this study was conducted to evaluate the antifungal potential of selected weed leachates against papaya anthracnose and explore their possible application as natural alternatives to synthetic fungicides in postharvest disease management.

MATERIALS AND METHODS

Experimental design and treatments

The in vitro and in vivo experiments were laid out in a Completely Randomized Design (CRD). The in vitro experiment consisted of 11 treatments, replicated three times, with four Petri plates per replication, 132 experimental units. The treatments included untreated control, a chemical check using Mancozeb at 3.6 g/L, and three concentrations of weed leachates from *Solanum torvum*, *Amaranthus viridis*, and *Lantana camara.* The concentrations used were 0.05%, 1%, and 5% (v/v) to evaluate the antifungal efficacy of the weed leachates across low, moderate, and high concentration levels. Specifically, the in vitro treatments were as follows: T1, Untreated control; T2, Mancozeb at 3.6 g/L; T3, 0.05% *Solanum torvum* leachate + PDA; T4, 1% *S. torvum* leachate + PDA; T5, 5% *S. torvum* leachate + PDA; T6, 0.05% *Amaranthus viridis* leachate + PDA; T7, 1% *A. viridis* leachate + PDA; T8, 5% *A. viridis* leachate + PDA; T9, 0.05% *Lantana camara* leachate + PDA; T10, 1% *L. camara* leachate + PDA; and T11, 5% *L. camara* leachate + PDA.

The in vivo experiment also followed a Completely Randomized Design and consisted of six treatments, replicated three times, with three papaya fruits per replication, 54 experimental units. The treatments included T1, untreated wounded control; T2, untreated inoculated control; T3, chemical check using Mancozeb at 3.6 g/L; T4, *Solanum torvum* leachate at 5% (v/v); T5, *Amaranthus viridis* leachate at 5% (v/v); and T6, *Lantana camara* leachate at 5% (v/v). The 5% concentration was used in the in vivo experiment based on its inclusion as the highest concentration evaluated under in vitro conditions. For the preparation of the weed leachates, 100 g of whole plant material was soaked in 200 mL of distilled water, following the standard solution of leachates described by Mandal and Tapaswi (1999).

Preparation of culture media

Potato Dextrose Agar (PDA) was used as the culture medium for the mycelial growth of *Colletotrichum* spp. (Mudiyansel et al., 2019). The medium was prepared at the Crop Research Laboratory, USeP-Mabini Campus (7.3275° N, 125.9926° E), following the standard procedure. Briefly, 250 g of potato was boiled and used as the potato extract, to which 20 g of dextrose, 20 g of agar, and distilled water were added to make a final volume of 1,000 mL. The prepared medium was then sterilized in a pressure cooker at 15 psi for 30 minutes before use.

Collection and isolation of the pathogen

Papaya fruits showing typical anthracnose symptoms were collected from the Tagum City market, Davao del Norte (7.44721° N, 125.80875° E). Fully-ripe papaya fruits were selected for pathogen isolation (Figure 1A). The infected fruits were placed in clean plastic containers (approximately 30 cm × 15 cm × 10 cm) and immediately transported to the Crop Protection Research Laboratory for analysis. Microscopic examination was then conducted to determine the association of the pathogen with the diseased tissues.

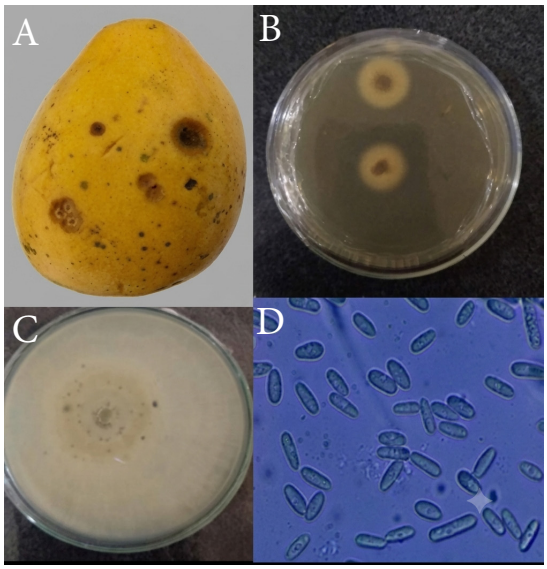

Figure 1. Anthracnose symptoms and culture characteristics of *Colletotrichum* spp.: (A) papaya fruit showing sunken brown lesions, (B) 3-day-old culture on PDA, (C) pure culture of *Colletotrichum* spp., and (D) microscopic appearance under a compound microscope.

The pathogen, *Colletotrichum* spp., was isolated using the tissue planting technique. Small tissue sections measuring approximately 2–3 mm were cut from the advancing margin of the infected papaya tissues and rinsed three times with sterile distilled water (SDW). The tissue sections were then planted equidistantly on plated Potato Dextrose Agar (PDA) medium. The cultures were incubated in an inverted position until fungal growth appeared and sporulation began, usually within 4 to 7 days. Microscopic mounts were prepared and examined under a compound microscope to confirm the identity of the pathogen and the purity of the culture.

Preparation of weed leachates

The weeds used as treatments for the control of *Colletotrichum* spp., namely *Solanum torvum*, *Amaranthus viridis*, *and Lantana camara*, were collected from the USeP Mabini Campus and placed separately in clean containers. The collected plant materials were weighed and washed twice with running tap water to remove surface debris, followed by rinsing with sterile distilled water. The samples were drained and air-dried at room temperature (approximately 25–28°C) for 12 hours. After drying, 100 g of finely chopped whole plant parts from each weed species were exposed to ultraviolet (UV) light for 2 hours for surface sterilization. All microbiological procedures were conducted aseptically inside a laminar flow hood to minimize contamination.

Aqueous weed leachates were prepared by soaking the sterilized leaf materials separately in 200 mL of sterile distilled water contained in sterile covered containers and maintaining them at room temperature (25–28°C) for four days. After soaking, the mixtures were filtered sequentially through a sterile wire mesh and sterile cheesecloth to obtain the aqueous weed leachates used as treatments in the experiment.

Figure 2. Chopped plant parts of (A) 1 – *Solanum torvum*, 2 – *Amaranthus viridis*, and 3 – *Lantana camara* soaked in distilled water, and (B) the corresponding weed leachates obtained.

In vitro test

The in vitro test was conducted to determine the efficacy of the different weed leachates against *Colletotrichum* spp. The poisoned food technique described by Grover and Moore (1962) was used to evaluate the fungicidal activity of the leachates against the pathogen. Sterile Potato Dextrose Agar (PDA) was amended with different concentrations of weed leachates, namely 0.05%, 1%, and 5%, and was aseptically poured into properly labeled Petri dishes. Mancozeb 80% WP, applied at the recommended rate, was used as the chemical check, while PDA without weed leachate served as the untreated control.

Approximately 15 mL of the amended medium was poured into each 90-mm Petri plate. After solidification, 5-mm fungal discs were obtained from the margin of a seven-day-old pure culture of *Colletotrichum* spp. using a sterile cork borer. Each fungal disc was aseptically transferred, with the mycelial side facing downward, onto the center of the prepared Petri plate. The inoculated plates were incubated at room temperature (27 ± 2°C) under natural light and dark conditions for seven days. The control plates were maintained under the same conditions using PDA without weed leachates, while the chemical check consisted of PDA amended with Mancozeb at the recommended rate. The experiment consisted of 11 treatments replicated three times, with four Petri plates per replication, giving a total of 132 experimental units. The antifungal activity of the weed leachates was evaluated by comparing the mycelial growth of *Colletotrichum* spp. in the treated plates with that of the untreated control and chemical check.

The diameter of the mycelial growth of *Colletotrichum* spp. was recorded at 3, 5, 7, and 9 days after incubation. Colony diameter was measured in millimeters using a ruler by taking the average of two perpendicular measurements: the longest diameter and the shortest diameter at right angles to each other. Mycelial growth inhibition was expressed as percentage inhibition and was computed at 3, 5, 7, and 9 days after incubation using the formula of Rao and Srivastava (1994).

$$\text{Mycelial growth inhibition (\%)} = \frac{GC - GT}{GC} \text{ X } 100$$

Where:

GC = mycelial colony growth in the control after the incubation period, excluding the diameter of the inoculum disc; and
GT = mycelial colony growth in the treatment after the incubation period, excluding the diameter of the inoculum disc.

In vivo test

Newly harvested mature papaya fruits were obtained directly from Vestige Papaya Farm, Sto. Tomas, Davao del Norte (7.5336° N, 125.6233° E). The test fruits were carefully selected to ensure uniform maturity and freedom from physical injuries, insect damage, and visible disease symptoms. The fruit samples were washed with distilled water, surface-sterilized using a cotton swab dipped in 70% ethyl alcohol, and air-dried at room temperature.

The fruits were inoculated with *Colletotrichum* spp. following the procedure of Awuah (1993), with some modifications. A wound measuring approximately 5 mm in diameter and 0.5 cm in depth was aseptically made on each fruit using a sterile cork borer. A mycelial disc taken from a 10-day-old pure culture of *Colletotrichum* spp. was placed into each wound. The inoculated fruits were then arranged in plastic trays and enclosed in humidified, inflated transparent polypropylene bags to maintain high relative humidity, which favors the infection and development of anthracnose caused by *Colletotrichum* spp. (Ploetz, 2003).

After inoculation, the fruits were incubated inside humidified transparent polypropylene bags for 48 hours at room temperature to allow pathogen establishment. Following incubation, the fruits were removed from the bags and dipped separately in 6 L of the respective weed leachate treatments (Figure 3A). The treated fruits were then air-dried for six hours at room temperature before further observation and evaluation. The fruits were then sprayed with 0.5% ethrel solution using a calibrated plastic spray bottle to induce uniform ripening. Ethrel was used to promote synchronized ripening by releasing ethylene, thereby ensuring uniform fruit maturity and consistent disease development during evaluation. After spraying, the fruits were placed in closed cardboard boxes for 48 hours to allow ripening and intensive respiration. Two days later, the fruits were removed from the boxes, arranged in plastic trays, and observed daily for disease development and fruit quality (Figure 3B).

The incubation period was determined by recording the number of days from inoculation until the first visible symptoms of anthracnose appeared. Disease severity was assessed using the 0–5 scale of Suharban et al. (1985), where 0 = 0% disease infection; 1 = 1–20% disease infection; 2 = 21–40% disease infection; 3 = 41–60% disease infection; 4 = 61–80% disease infection; and 5 = 81–100% disease infection. The Disease Severity Index (DSI) was computed using the following formula:

$$\% \text{ DI} = \frac{0n_0+1n_1+2n_2+3n_3+4n_4+5n_5\ldots}{5(N)} \text{ X } 100$$

Where:

%DI = percentage disease index;
0n0+1n1…= refers to the samples with a rating of 0, 1, 2, 3, 4, 5;
N = total number of samples; and
5 =highest rating used.

Visual quality rating (VQR) was recorded daily using the scale of Amarakoon et al. (1999), where 9 = excellent, no defects; 7 = good, slight defects; 5 = fair, moderate defects and limit of marketability; 3 = poor, serious defects and limit of edibility; and 1 = non-edible. Observations were continued until the fruits reached VQR 3, indicating poor quality with serious defects and limited edibility. The degree of fruit shriveling was also evaluated using the scale of Nunes et al. (2007), where 1 = no signs of shriveling; 2 = minor signs of shriveling; 3 = moderate shriveling; 4 = severe shriveling; and 5 = extreme shriveling.

Figure 3. Papaya fruits soaked in (A) 1 – distilled water, 2 – Mancozeb solution, 3 – *Solanum torvum* leachate, 4 – *Amaranthus viridis* leachate, and 5 – *Lantana camara l*eachate; and (B) the experimental set-up.

Statistical analysis

The collected data were homogenized and tested for normality using the Shapiro–Wilk test through the Statistical Tool for Agricultural Research (STAR) version 1.0. Data that satisfied the assumptions of normality were analyzed using Analysis of Variance (ANOVA) based on a Completely Randomized Design (CRD). When significant differences among treatment means were detected at the 5% level of significance ($p \leq 0.05$), mean comparisons were performed using Tukey's Honest Significant Difference (HSD) test. For ordinal data, a nonparametric Kruskal–Wallis test was used to determine significant differences among treatments. When significant differences were observed, treatment comparisons were further analyzed using the Mann–Whitney U test.

RESULTS

Colony diameter and growth inhibition

The in vitro experiment was conducted to determine the efficacy of different concentrations of weed leachates against *Colletotrichum* spp. using the poisoned food technique. Results showed that the weed leachates of *Solanum torvum*, *Amaranthus viridis*, and *Lantana camara* reduced the colony diameter and inhibited the mycelial growth of *Colletotrichum* spp. at varying levels across the observation periods. Mancozeb, used as the chemical check, consistently showed complete inhibition of mycelial growth, with 100% growth inhibition from 3 to 9 days of incubation (DOI).

Table 1. Colony diameter (CD) and percentage growth inhibition (% GI) of *Colletotrichum* spp. as affected by the different treatments at 3, 5, 7, and 9th DOI.

Treatment	Observation period							
	3rd DOI**		5th DOI**		7th DOI**		9th DOI**	
	CD (mm)	%GI	CD (mm)	%GI	CD (mm)	%GI	CD (mm)	%GI
T1- Untreated Control	22.33	-	46.54	-	62.88	-	75.13	-
T2- Mancozeb at 3.6 g/L	0.00	100a	0.00	100a	0.00	100a	0.00	100a
T3- 0.05% *Solanum torvum*	17.42	21.99de	39.88	14.31cde	56.46	10.21e	72.88	2.99e
T4- 1% *Solanum torvum*	16.47	26.24d	40.86	12.20de	54.99	12.55e	64.50	14.15e
T5- 5% *Solanum torvum*	14.33	35.83bc	29.92	35.71b	35.08	42.24b	34.29	53.36b
T6- 0.05% *Amaranthus viridis*	18.83	15.67e	41.42	11.0e	55.58	11.61e	63.04	16.09e
T7- 1% *Amaranthus viridis*	16.29	27.05cd	36.88	20.76c	54.96	12.60e	62.83	16.37e
T8- 5% *Amaranthus viridis*	16.13	27.27bcd	31.42	32.49b	44.13	29.82b	36.29	51.70b
T9- 0.05% *Lantana camara*	16.71	25.17de	36.83	20.86c	54.08	13.99de	65.21	13.20de
T10- 1% *Lantana camara*	15.25	31.37bcd	39.29	15.58cde	50.00	20.48cd	56.88	20.30cd
T11- 5% *Lantana camara*	14.17	14.17b	37.71	18.9cd	48.38	23.06c	53.04	29.40c
p-value	-	0.00	-	0.00	-	0.00	-	0.00

**Significant at p<0.01 based on Analysis of Variance (ANOVA) using Tukey's Honest Significant Difference (HSD) Test; Means within the same column followed by the same superscript letter are not significantly different; and DOI= Days of incubation.

At 3rd DOI, all weed leachate treatments reduced the mycelial growth of the pathogen compared with the untreated control (p<0.05). Among the weed leachates, the highest inhibition was observed in 5% *Solanum torvum*, with 35.83% growth inhibition, followed by 1% *Lantana camara* with 31.37% and 5% *Amaranthus viridis* with 27.27%. The untreated control recorded the highest colony diameter of 22.33 mm, indicating unrestricted growth of the pathogen. This suggests that even at the early stage of incubation, the weed leachates exhibited antifungal activity against *Colletotrichum* spp. At 5th DOI, the inhibitory effect of the weed leachates remained evident. The 5% Solanum torvum treatment still showed the highest inhibition among the weed leachates, with 35.71% growth inhibition, followed by 5% *Amaranthus viridis* with 32.49%.

At 7th DOI, 5% *Solanum torvum* continued to show the greatest inhibitory effect among the weed leachate treatments, with 42.24% growth inhibition. This was followed by 5% *Amaranthus viridis* with 29.82% and 5% *Lantana camara* with 23.06%. These results indicate that the 5% concentration consistently performed better than the lower concentrations, suggesting that higher concentrations of weed leachates were more effective in suppressing the mycelial growth of *Colletotrichum* spp. At 9th DOI, the inhibitory effect of the weed leachates was still observed, although the degree of inhibition varied among treatments. The highest growth inhibition was recorded in 5% *Solanum torvum* at 53.36%, followed closely by 5% *Amaranthus viridis* at 51.70%. The 5% *Lantana camara* treatment showed 29.40% growth inhibition, indicating moderate antifungal activity. In contrast, the lowest inhibition among the weed leachate treatments was observed in 0.05% *Solanum torvum*, with only 2.99% growth inhibition. These findings show that the effectiveness of the weed leachates was generally concentration-dependent, with the 5% concentration giving the highest inhibition for all weed species.

Incubation and disease severity

The in vivo experiment was conducted to further evaluate the antifungal efficacy of the 5% weed leachates against anthracnose of papaya caused by *Colletotrichum* spp. The mean number of days to symptom appearance and the disease severity of inoculated papaya fruits as influenced by the different treatments are presented in Table 2. Results showed that the incubation period was not significantly affected by the treatments (p>0.05). However, numerical differences were observed among treatment means. Fruits treated with 5% *Amaranthus viridis* leachate had the longest incubation period (3.78 days), followed by the Mancozeb (3.45 days) and 5% *Solanum torvum* leachate (3.00 days), whereas the untreated inoculated fruits showed the shortest incubation period (2.44 days). This trend suggests that some treatments, particularly *A. viridis*, may have delayed symptom development, although the effect was not statistically significant.

Table 2. Incubation and disease severity of *Colletotrichum* spp. as affected by different levels of weed leachates concentration.

Treatments	Incubation period	Disease severity		
	Mean^{ns}	3DAI**	5DAI**	7DAI*
T1- Untreated: Wounded	3.56	17.13a	26.01a	43.04a
T2- Untreated: Inoculated	2.44	41.82b	54.76b	78.43b
T3- Mancozeb at 3.6 g/L	3.45	15.00a	32.35a	44.37a
T4- 5% *Solanum torvum*	3.00	33.86b	48.18b	65.37ab
T5- 5% *Amaranthus viridis*	3.78	18.85a	33.82a	47.08a
T6- 5% *Lantana camara*	2.56	28.49b	49.55b	73.06ab
p-value	0.06	0.01	0.01	0.02

^{ns}Not significant; **Significant at p=0.01; *Significant at *p*<0.05 based on Analysis of Variance (ANOVA) using Tukey's Honest Significant Difference (HSD) Test. Means within the same column followed by the same superscript letter are not significantly different; and DAI=Days after inoculation.

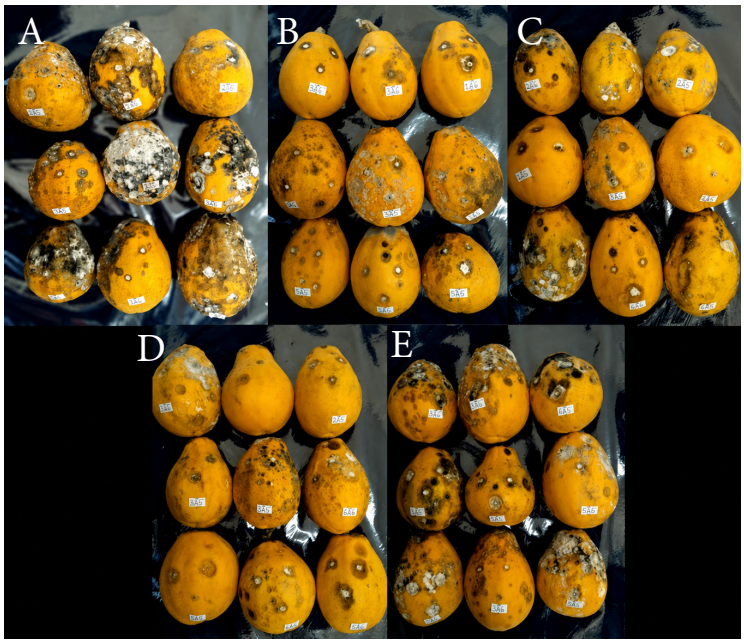

Figure 4. Papaya fruits treated with different leachates at 7 days after treatment: (A) Distilled water-inoculated control, (B) Mancozeb, (C) *Solanum torvum*, (D) *Amaranthus viridis*, and (E) *Lantana camara*.

In contrast, disease severity was significantly influenced by the treatments, with highly significant differences among treatments observed on the 3rd and 5th days after inoculation (DAI) ($p = 0.01$) and significant differences on the 7th DAI ($p < 0.05$). At 3rd DAI, the untreated inoculated fruits had the highest disease severity (41.82%), while the chemical check had the lowest (15.00%). Among the weed leachates, 5% *Amaranthus viridis* resulted in the lowest disease severity (18.85%), followed by 5% *Lantana camara* (28.49%) and 5% *Solanum torvum* (33.86%). This indicates that *A. viridis* was the most effective weed leachate in reducing disease development during the early stage of infection.

A similar trend was observed at 5th DAI. The untreated inoculated fruits remained the most severely infected, with 54.76% disease severity. Among the treated fruits, the chemical check recorded the lowest severity (32.35%), closely followed by 5% *Amaranthus viridis* (33.82%). On the other hand, 5% *Solanum torvum* and 5% *Lantana camara* had higher disease severity values of 48.18% and 49.55%, respectively. These results indicate that *A. viridis* was more effective than the other two weed leachates in suppressing anthracnose development and was comparable to the chemical check.

At 7th DAI, disease severity further increased in all treatments, but clear differences among treatments were still evident. The untreated inoculated fruits exhibited the highest disease severity at 78.43%, indicating severe infection and rapid disease progression in the absence of control measures. Among the weed leachates, 5% Amaranthus viridis consistently produced the lowest disease severity (47.08%), which was numerically close to the chemical check (44.37%). In comparison, fruits treated with 5% *Solanum torvum* and 5% *Lantana camara* had higher disease severity values of 65.37% and 73.06%, respectively. These findings demonstrate that *A. viridis* was the most effective weed leachate in reducing anthracnose severity under in vivo conditions.

The visual observations shown in Figure 4 support the disease severity data. Fruits treated with distilled water and inoculated with the pathogen showed severe anthracnose symptoms, while fruits treated with the chemical check had the least visible infection. Among the weed leachate treatments, papaya fruits treated with 5% *Amaranthus viridis* showed fewer and less severe lesions than those treated with *Solanum torvum* and *Lantana camara*. This visual evidence further confirms the superior performance of *A. viridis* in suppressing anthracnose development.

Visual quality and degree of shriveling

The effects of weed leachates on the visual quality and degree of shriveling of papaya fruits are presented in Table 3. Significant differences in visual quality were observed at 3rd , 5th, and 7th days after treatment (DAT) based on the Kruskal–Wallis test followed by Mann–Whitney U test comparison ($p < 0.05$). Visual quality progressively declined during storage in all treatments; however, fruits treated with weed leachates and Mancozeb maintained better appearance compared with the untreated inoculated control.

Among the treatments, fruits treated with Mancozeb and 5% *A. viridis* consistently recorded higher visual quality ratings. At 3rd DAT, Mancozeb and *A. viridis* obtained visual quality ratings of 8.11 and 8.33, respectively, compared with 6.11 in the untreated inoculated control, showing a good to moderate defects which limits marketability. Similar trends were observed at 5th DAT, where Mancozeb and *A. viridis* maintained ratings of 6.56 and 6.11, respectively, while the untreated inoculated fruits declined to 3.22. At 7th DAT, fruits treated with Mancozeb and *A. viridis* still exhibited comparatively higher ratings of 3.44, indicating delayed deterioration and prolonged marketability. In contrast, untreated inoculated fruits reached the limit of edibility earlier, with the lowest rating of 1.00 at 7th DAT. Fruits treated with *S. torvum* and *L. camara* showed intermediate responses, with moderate deterioration observed during storage.

Significant differences in the degree of shriveling were likewise observed at 3rd, 5th, and 7th DAT. The untreated inoculated fruits consistently recorded the highest shriveling ratings, particularly at 5th and 7th DAT, with values of 3.22 and 3.89, respectively, indicating severe moisture loss and tissue collapse associated with anthracnose infection. In contrast, fruits treated with Mancozeb and *A. viridis* exhibited lower shriveling ratings throughout the observation period. At 7th DAT, Mancozeb and *A. viridis* recorded shriveling ratings of 1.78 and 2.44, respectively, demonstrating better maintenance of fruit firmness and external appearance compared with the untreated inoculated control.

Table 3. Visual quality and degree of shriveling of papaya fruit as affected by different levels of weed leachates concentration.

Treatment	Visual quality			Degree of shriveling		
	3Dat**	5Dat**	7Dat*	3Dat*	5Dat*	7Dat*
T1- Untreated: Wounded	8.56a	7.22a	5.00a	1.00a	1.33a	1.67a
T2- Untreated: Inoculated	6.11c	3.22c	1.00c	1.78b	3.22b	3.89c
T3- Mancozeb at 3.6 g/L	8.11a	6.56a	3.44b	1.00a	1.22a	1.78a
T4- 5% *Solanum torvum*	6.78b	4.56b	1.22c	1.11a	1.67a	2.55b
T5- 5% *Amaranthus viridis*	8.33a	6.11a	3.44b	1.00a	1.22a	2.44b
T6- 5% *Lantana camara*	6.11c	4.11b	1.67c	1.33a	1.89a	1.67a
p-value	0.01	0.01	0.02	0.04	0.02	0.04

[ns]Not significant; **Significant at p=0.01; *Significant at p<0.05 based on Kruskal–Wallis test using Mann–Whitney U test; Means within the same column followed by the same superscript letter are not significantly different; and DAT=Days after treatment.

DISCUSSION

The results of the in vitro experiment demonstrated that the weed leachates of *Solanum torvum, Amaranthus viridis*, and *Lantana camara* inhibited the mycelial growth of *Colletotrichum* spp. Although colony diameter increased as incubation progressed, fungal growth in treated plates remained lower than in the untreated control, indicating the presence of bioactive compounds with antifungal activity. Among the treatments, 5% *S. torvum* exhibited the highest inhibition, followed closely by 5% *A. viridis*, suggesting a concentration-dependent response in which higher concentrations resulted in greater suppression of fungal growth. Similar findings were reported by Dellavalle et al. (2011), who observed that the antifungal activity of medicinal plant extracts against phytopathogenic fungi increased with extract concentration. This observation is also consistent with the findings of Banso et al. (1999), who reported that higher concentrations of plant-derived extracts produced greater inhibition of fungal growth.

The strong inhibitory effect of *S. torvum* may be associated with its pharmacologically active constituents, including steroidal glycosides, chlorogenone derivatives, spirostanol oligoglycosides, and methyl caffeate, which have been reported to possess antimicrobial properties (Lu et al., 2011; Balachandran et al., 2012). These compounds may inhibit fungal development by altering cell membrane permeability, disrupting hyphal growth, and interfering with essential metabolic processes required for fungal proliferation. Phenolic compounds and glycoalkaloids from Solanum species have also been reported to induce leakage of intracellular components and inhibit spore germination in phytopathogenic fungi (Afroz et al., 2020; El-Nagar et al., 2020).

Likewise, the antifungal activity of *A. viridis* may be attributed to its rich phytochemical composition, including saponins, tannins, flavonoids, alkaloids, phenolics, and triterpenoids (Bharathi et al., 2022). These secondary metabolites are known to suppress fungal growth through multiple mechanisms, such as disruption of membrane integrity, inhibition of spore germination, and impairment of mitochondrial function (El-Sakhawy et al., 2025; Hosee et al., 225). Carminate et al. (2012) similarly reported that *A. viridis* extracts exhibited antimicrobial activity against fungal pathogens such as *Colletotrichum* sp. and Fusarium solani.

Although *L. camara* showed comparatively lower inhibition, it still reduced mycelial growth of *Colletotrichum* spp., confirming its fungitoxic potential. This observation agrees with the findings of Prasad and Anamika (2015) and Mudiyansel et al. (2019), who reported suppression of mycelial growth and conidial formation of *Colletotrichum* spp. by *L. camara* extracts.

Under in vivo conditions, the weed leachates influenced anthracnose development in papaya fruits. Although the incubation period was not significantly affected, fruits treated with 5% *A. viridis* showed delayed symptom appearance compared with the untreated inoculated fruits, suggesting partial suppression of pathogen establishment during the early stages of infection. Disease severity, however, was significantly reduced by the treatments at 3, 5, and 7 days after inoculation. Untreated inoculated fruits consistently exhibited the highest disease severity, confirming the aggressive nature of *Colletotrichum* spp. as a postharvest pathogen of papaya. This supports previous reports that anthracnose is among the most destructive postharvest diseases affecting papaya during storage and marketing (Rampersad, 2011; Valenzuela et al., 2015).

Among the weed leachates evaluated, 5% *A. viridis* was the most effective in reducing disease severity under fruit conditions and showed results numerically comparable to the chemical check. Interestingly, although *S. torvum* produced the greatest inhibition in vitro, *A. viridis* performed better in vivo. This variation may be associated with the complexity of fruit-pathogeninteractions, including factors such as wound response, fruit surface characteristics, ripening stage, and the interaction between plant metabolites and host tissues. The effectiveness of *A. viridis* may also be linked to its phenolic and antimicrobial compounds, which may help suppress pathogen growth and delay disease progression on the fruit surface (Kumari et al., 2018; Malik et al., 2016).

Fruit quality parameters were likewise influenced by the treatments. Untreated inoculated fruits rapidly lost marketable quality due to severe lesion development, tissue breakdown, and shriveling. In contrast, fruits treated with 5% *A. viridis* and the mancozeb maintained better visual quality up to 7 days after inoculation. This suggests that reduced disease development contributed to delayed fruit deterioration and preservation of acceptable appearance. The ability of *A. viridis* to maintain fruit quality may be associated with its flavonoids, phenolics, alkaloids, and tannins, which possess antifungal and antioxidant properties that may help slow pathogen activity and tissue deterioration (Kumari et al., 2018; Sarker et al., 2022).

The rapid deterioration observed in untreated inoculated fruits may also be associated with increased ethylene production triggered by pathogen infection. Papaya is a climacteric fruit, and infection or injury can accelerate ripening and senescence through enhanced ethylene synthesis. Yang and Hoffman (1984) reported that ethylene production increases in response to wounding and microbial attack, while Daundasekera et al. (2003) noted that *Colletotrichum* species may stimulate ethylene-related processes that hasten tissue softening and decay. Consequently, severe anthracnose infection likely accelerated ripening and quality deterioration in untreated fruits.

Similarly, shriveling progressively increased during storage, particularly in untreated inoculated fruits. This may be attributed to increased moisture loss and tissue collapse resulting from severe infection. Fruit shriveling is commonly associated with loss of cell turgor and structural weakening due to water loss (Ciofini et al., 2022). Infected tissues generally become more permeable, resulting in faster dehydration compared

with healthy tissues. In the present study, fruits treated with weed leachates, especially *A. viridis*, exhibited lower shriveling, indicating that disease suppression also contributed to reduced moisture loss and improved maintenance of fruit quality.

CONCLUSION

This study demonstrated that weed leachates from *Solanum torvum*, *Amaranthus viridis*, and *Lantana camara* possess antifungal activity against *Colletotrichum* spp., the causal agents of papaya anthracnose. Under in vitro conditions, inhibition of mycelial growth increased with concentration, with 5% *S. torvum* exhibiting the highest antifungal activity among the weed leachates tested. In vivo evaluation further revealed that 5% *A. viridis* was the most effective treatment in reducing disease severity, delaying symptom development, minimizing shriveling, and preserving the visual quality of papaya fruits. Although Mancozeb remained the most effective treatment overall, the findings highlight the promise of *A. viridis* leachate as a natural and sustainable alternative for the postharvest management of papaya anthracnose. Its local availability, low cost, and antifungal efficacy suggest its suitability for small-scale and environmentally sustainable papaya production systems.

However, the study was conducted under laboratory conditions using a limited number of fruit samples, which may not fully represent the natural variability in fruit physiology, ripening behavior, and disease development under commercial postharvest conditions. Therefore, further studies are recommended to identify the active compounds responsible for the antifungal activity of *A. viridis*, determine its mode of action, and evaluate its effectiveness using larger sample populations, commercial storage and marketing conditions.

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AUTHOR CONTRIBUTIONS

A. J. M. O: Conceptualization, Investigation, Writing (Original Draft). J. C. B: Writing (Review and Editing). R. Z. R: Supervision, Resources, Validation. M. H. J: Conceptualization; S. S. B: Conceptualization.

DECLARATIONS

Informed consent statement

This study was conducted in accordance with standard ethical guidelines for agricultural research. No human participants or animal subjects were involved; therefore, informed consent was not required. All procedures involving plant materials and biological agents, including plant pathogens, were performed responsibly and with proper laboratory precautions to prevent contamination and unintended pathogen spread. Data were accurately recorded, securely stored, and reported with integrity.

Conflict of interest

The author declares no conflict of interest, whether financial or non-financial, related to this manuscript. No affiliations, funding sources, or personal relationships influenced the conduct, analysis, or reporting of the research.

AI Declaration

The authors declare that no Artificial Intelligence (AI) or AI-assisted technologies were used in the preparation of this manuscript.

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