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Dual Role of Triazole Fungicides in Managing Alternaria Blight and Promoting Growth in Groundnut (*Arachis hypogaea* L.)

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Abstract

Alternaria leaf blight (ALB) is a major constraint to groundnut production, particularly in North Gujarat, where its incidence has intensified in recent years due to changing climatic conditions. Effective and sustainable disease management requires fungicides that not only suppress the pathogen but also promote plant growth. To identify such options, field experiments were conducted during 2016–2018 to evaluate the bioefficacy of nine fungicides, including five systemic, two contact, and two combination formulations. Among these, propiconazole 25 EC, tebuconazole 25 WG, and carbendazim 50 WP were the most effective in reducing disease intensity and slowing disease progression. The highest pod and haulm yields were recorded in plots treated with tebuconazole 25 WG, followed by propiconazole 25 EC and carbendazim 50 WP. However, the highest cost–benefit ratio was observed with carbendazim 50 WP, followed by propiconazole 25 EC and tebuconazole 25 WG. In addition, propiconazole 25 EC and tebuconazole 25 WG exhibited notable plant growth-promoting effects, enhancing plant height, root length, and chlorophyll content. Based on these findings, the application of propiconazole 25 EC or tebuconazole 25 WG is recommended for the effective and economical management of ALB in groundnut.

Keywords: *Arachis hypogaea*; Alternaria leaf blight; propiconazole; tebuconazole; plant growth promotion; disease suppression

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1. Introduction

Groundnut (*Arachis hypogaea* L.) is one of the most important oilseed crops in India, covering nearly half of the area under oilseeds. Gujarat has been the leading state, producing around 36 percent of the country's groundnut for a decade [1]. The area under groundnut cultivation is increasing, especially in north Gujarat, because the farming communities have adopted remunerative cropping sequences. i.e., Kharif groundnut, Rabi potato, and summer—bajra/groundnut [2]. Due to this, the pests and pathogens are harbored by the host around the year. Hence, problems of various pests and diseases are also increasing. This crop suffers many foliar, stem, and root diseases. Among them, foliar diseases like Alternaria leaf blight [3] and early and late leaf spots [4,5] are the most serious diseases of groundnut. The Alternaria leaf blight in groundnut is caused by different species of Alternaria *viz.*, *A. alternata* [6,7], *A. tenuissima* [8,9], and *A. archchidis* [10], with *A. alternata* being one of the dominant culprits. The disease is characterized by dark brown to black spots appearing from the margin of leaves, often surrounded by a yellow halo [11]. Gradually, these necrotic lesions expand, covering large areas on the leaves with loss of chlorophyll, resulting in rapid defoliation and premature death of the plant with reduced yield. In severe cases, lesions may also develop on the pods, leading to reduced quality of the nuts [12]. This disease is highly prevalent in Gujarat, which damages foliage and badly affects the crop responsible for causing huge crop loss [13]. Furthermore, the intensification of the modern agroecosystem with the adoption of modern technological advancements like sprinkler irrigation by local farmers creates a conducive environment for these foliar pathogens for their reproduction and dispersal. Furthermore, climate change has a severe impact on the arid agriculture of western India. Temperature rise favors the faster pathogen growth and sporulation by shortening the incubation period; thus, expansion of foliar diseases to non-traditional groundnut areas is very common. The higher temperatures with increased humidity and altered precipitation patterns during the *Kharif*/rainy season accelerate the severity of Alternaria blight in groundnut [14]. These altered weather conditions can promote disease outbreaks if they prevail during critical growth stages of the groundnut. Therefore, it is necessary to intervene in the fungal pathogenesis by employing various fungicides, including contact fungicides like mancozeb, propineb, chlorothalonil, etc., and systemic fungicides like carbendazim, triazoles, etc.

Although triazole fungicides are widely recognized for their effectiveness in controlling fungal diseases such as Alternaria leaf blight (ALB) in groundnut, their plant growth-promoting (PGP) properties remain underexplored, especially under field conditions in semi-arid regions like North Gujarat. The existing study primarily focuses on their fungicidal efficacy, i.e., evaluating the efficacy of selected triazole fungicides in reducing the incidence and severity of *Alternaria* blight in groundnut under field conditions, along with the exploration of their hormonal modulation effects, i.e., the plant growth regulatory role of triazole fungicides through biochemical and physiological indicators (e.g., enhancing chlorophyll synthesis, root development, and overall biomass). Furthermore, limited comparative analyses are available to quantify the dual role of triazoles in both disease suppression and growth enhancement relative to economic outcomes such as cost–benefit ratios. A systematic assessment of these dual benefits, particularly over multiple seasons and agro-climatic conditions, is lacking. Hence, there is a need for integrated studies that elucidate the mechanistic basis of triazole-induced plant growth promotion along with their efficacy in sustainable ALB management.

2. Materials and Methods

2.1. Collection of Disease Samples and Identification of Pathogen

Groundnut plants that had typical symptoms of Alternaria blight in leaves were collected from the Agronomy Instructional Farm, Sardarkrushinagar Dantiwada Agricultural University, Sardarkrushinagar, and taken right away to the lab for a preliminary evaluation under a microscope, after which the pathogen was isolated from infected leaves using a tissue isolation procedure on a PDA. A sterile blade was used to chop diseased leaves into tiny bits. After rinsing the pieces in sterile water, they were treated for 45 s with a 1.0 percent NaOCl solution to disinfect them. As a result, the aseptic transfer of the acquired disinfected pieces onto PDA plates was carried out promptly after three rounds of washing with sterilized distilled water. Petri plates that had been inoculated were incubated at 27 ± 2 °C. After 48 h of incubation, light brownish-black mycelium development was seen on and surrounding the infected pieces. After mycelial development was noticed, a fungal culture was produced, which was then further refined using a single spore isolation technique. The pure culture was examined visually for morphology characteristics, viz., length and width of conidia along with septation and beak length, the structure of conidiophores, etc., under high power (×400) magnification. The morphological characteristics of the fungus were recorded and compared with the standard literature for identification of the pathogen. The culture was transferred periodically and maintained on PDA slants at 4 °C temperature. Further confirmation was performed by the partial ribosomal DNA sequence amplification using ITS1 (5′TCCGTAGGTGAACCTGCGG3′) and ITS4 (5′TCCTCCGCTTATTGATATGC3′) primers [15]. The amplified regions were sequenced, and the sequences were submitted to the NCBI database.

2.2. Funigide Detail

In this study, nine different fungicides were used, out of which two were non-systemic, five were systemic fungicides, and two were combi-fungicides. Among non-systemic fungicides, Metiram 70 WG (Polyram, BASF India Ltd., Mumbai, India) and Mancozeb 75 WP (Indofil M-45, Indofil Industries Ltd., Mumbai, India) were selected. On the other hand, among systemic fungicides, hexaconazole 5 EC (Contaf TATA Rallis, Mumbai, India), difenoconazole 25 EC (Score, Syngenta India Ltd., Pune, Maharashtra, India), propiconazole 25 EC (Tilt, Syngenta India Ltd., Pune, Maharashtra, India), tebuconazole 25 WG (Caviet, Excel Crop Care Limited, Mumbai, India), and carbendazim 50 WP (Bavistin, Crystal Crop Protection Ltd., New Delhi, India) were chosen. The combination fungicides used were carbendazim12%+ mancozeb 63% WP (SAAF, UPL India Ltd., Mumbai, India) and pyraclostrobin 133 g/L + epoxiconaxole 50 g/L SE (Opera, BASF India Ltd., Mumbai, India). The test fungicide formulations were purchased from their respective manufacturers. The details of tested fungicides on the formulation, dosage, site of action, fungicide symbol, and FRAC code are provided in Table 1.

Table 1. Description of fungicides used for evaluation against *A. alternata*.

Fungicides	a.i./ha	Dose/ha	Fungicide Symbol	Chemical Group	Target Site [1]	FRAC Code [2]
Difenoconazole 25 EC	125 mL	500 mL	DIF	Triazole	SBI	3
Hexaconazole 5 EC	75 mL	1500 mL	HEX	Triazole	SBI	3
Propiconazole 25 EC	125 mL	500 mL	PRO	Triazole	SBI	3
Tebuconazole 25 WG	125 gm	500 gm	TEB	Triazole	SBI	3
Carbendazim 50 WP	250 gm	500 gm	CAR	Benzimidazole	TBI	1
Mancozeb 75 WP	1.125 kg	1.5 kg	MAN	Dithiocarbamate	MSC	M03
Metiram 70 WG	1400 gm	2000 gm	MET	Dithiocarbamate	MSC	M03
Pyraclostrobin133 g/L + Epoxiconaxole 50 g/L SE	114.37 mL	625 mL	PYR + EPO	Strobilurin + Triazole	QoI + SBI	11 + 3
Carbendazim12% + Mancozeb 63% WP	375 gm	500 gm	CAR + MAN	Benzimidazole + Dithiocarbamate	TBI + MSC	1 + M03

Note: [1] SBI (sterol biosynthesis inhibitor), TBI (β-tubulin biosynthesis inhibitor), QoI (quinone outside Inhibitors), MSC (multi-site action); [2] FRAC (Fungicide Resistance Action Committee) code list 2021.

2.3. Field Layout and Spray Detail

The field experiments were conducted during the *Kharif* season in 2016, 2017, and 2018 at Agronomy Instructional Farm, S. D. Agricultural University, North Gujarat Agro-climatic Zone-IV (AES-1). Groundnut variety GG-2 was sown in a 3.60 m × 5.0 m gross plot and a 2.70 m × 4.0 m net plot size, adopting the spacing of 45 cm × 10 cm and seed rate of 120 kg/ha. A total of ten treatments, including control, were arranged in a randomized complete block design (RBD) and replicated thrice. Other agronomic practices and nutrient applications were followed as per the standard package of practices of S. D. Agricultural University (SDAU), Sardarkrushinagar, Gujarat, India. The meteorological data (e.g., rainfall, humidity) of the trial seasons were also recorded (Table S1).

Nine different fungicides were used for the management of leaf spot diseases (Table 1). The first spray was given at the initiation of foliar disease during the experiments, and the remaining two sprays were given at 15-day intervals subsequently. Ten treatments, including one control, were imposed with three replications in the randomization block design. Fungicides were applied using an Electro Battery Sprayer (Aspee AEL001/8AHBR) with 16 L capacity. The sprayer was calibrated to deliver 500 L/ha at the flow rate of 2 L/min using an adjustable nozzle with a discharge pressure of 2.8 kg/sq. cm. The spray was performed during the afternoon. The first spray was scheduled in the 3rd–4th week, i.e., the early growth stage with the onset of disease; thereafter, spraying was performed in the 6th–7th week, i.e., the vegetative growth stage, and the 9th–10th week, i.e., the flowering and pod development stage. The rainfall was avoided for 24 h after the spray (by adjusting the spraying date).

2.4. Disease Assessment and Yield Estimation

With the onset of the disease, twenty plants per plot were randomly selected and tagged for observations. Observations were recorded just before each spray up to harvesting. Alternaria leaf blight severity was recorded based on the percent leaf area affected in the plant canopy. The selected plants were scored individually, taking into account the leaf area damaged by the disease, and categorized into a 1–9 rating scale as proposed for Cercospora leaf spot in groundnut [16]. The percent disease intensity was calculated as the formula suggested by Horsefall and Heuberger [17], and AUDPC was calculated as per the formula of Shaner and Finney [18]. The pod yield and fodder/haulm yield were also recorded separately 7 days after harvesting. The pod and haulm of each plot were dried under shade after harvesting. In 2017, the recorded yield differences were influenced by the occurrence of Aspergillus collar rot, a soil-borne disease that can cause seedling mortality and poor crop stand.

2.5. Measurement of Plant Growth and Chlorophyll

To determine the effect of fungicides on plant growth, ten plants were randomly selected from each plot and their height and root length was measured in cm from the base of the plant to the tip of each end. The average plant height and root length were calculated. Further, total chlorophyll content was measured using a portable MC-100 Chlorophyll Concentration Meter (Apogee Instruments Inc., Logan, UT, USA). Three fully opened leaves were randomly selected from each plant at a specific height zone. The total chlorophyll content of the top leaflets of each three leaves was recorded and the average values of the plant were calculated. The mean value of such ten plants was measured as the chlorophyll content (µmole m^{-2}) of the relevant treatment. The measurement was taken in three replicated trials during the pod-filling stage.

2.6. Statistical Analysis

The field experiments were conducted in a randomized block design with ten treatments in three replicated trials. To achieve normal distribution for field data, the percentage of disease severity data was transformed using arcsine rules. Further statistical analysis was performed by Duncan's New Multiple Range Test (DNMRT) at the 5% level using SPSS V.20 software. The data in tables was reported in transformed and untransformed units, with CD values to differentiate treatment means at 5% level of significance. Bar charts for chlorophyll content and plant growth parameters were generated using the GRAPES (General R-based Analysis Platform Empowered by Statistics) web tool [19] to compare treatment efficacy with the control. A correlation matrix was formed with a correlogram using different disease severity, yield, and growth parameters to establish the hypothesis.

3. Results

3.1. Fungal Pathogen

Fungal culture was isolated from the infected leaf samples of groundnut sowing typical leaf blight symptoms starting from the margin and tip (Figure 1). The pathogen was initially identified as *Alternaria* sp. by comparing the morphological and microscopic observation of the fungal culture with the literature. After seven days of incubation, the colony diameter of the isolated fungus was recorded to be 85.00 mm, and the growth of mycelia was slightly fluffy and grayish-white to gray-brown in color (Figure 2A). The microscopic study of the fungus revealed that the mycelium of the fungus was initially hyaline, which later became pale brown to olivaceous brown or smoky. The hyphae were septate and irregularly branched, and the conidia were clavate to obclavate, muriform with short septate beaks (5.10 µm), 1–3 longitudinal septa and 3–7 transverse septa, constricted walls (Figure 2B), and scarred at base and apex, measuring 43.80 µm × 12.18 µm; they were mostly produced in chains of 3–10 (Figure 2C). Based on the size and septation of spores, it was identified as *Alternaria alternata*. Their identity was further confirmed based on the ribosomal DNA partial sequence submitted in the NCBI database with accession number PV639008 (*Alternaria alternata* isolate SKN). The pathogenicity of the fungus was proved by artificial inoculation of groundnut seedlings. The typical leaf spot symptoms were observed on foliage 7 days after incubation; it revealed that *A. alternata* was pathogenic to groundnut.

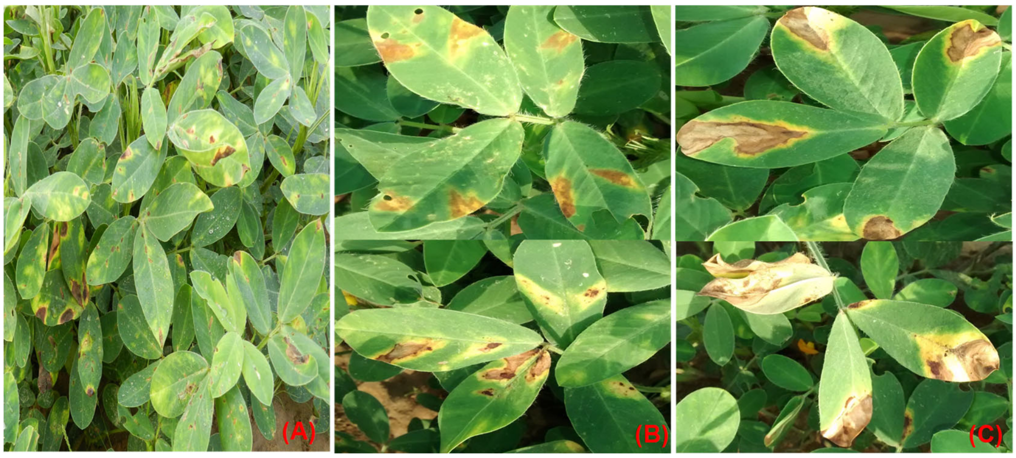

Figure 1. Symptomatology of Alternaria leaf blight of groundnut. (**A**) Irregular yellow patches with few necrotic spots at the initial stage. (**B**) Typical brown patches start from the margin of the leaf lamina. (**C**) The patches enlarge gradually, resulting in typical leaf blight symptoms.

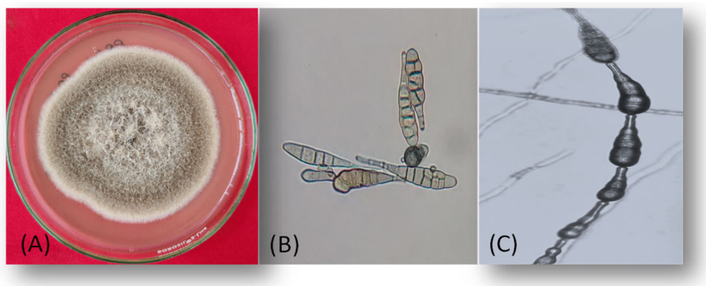

Figure 2. Isolation and identification of *Alternaria alternata* causing leaf blight in groundnut. (**A**) Gray-brown colony grown in PDA media; (**B**) typical dictyospore (×400) with short beak produced in a small chain of 3–10 conidia; and (**C**) is the key identifying feature.

3.2. Bio-Efficacy of Fungicides Against Alternaria Leaf Blight Disease

In all three seasons, initial ALB symptoms were observed on the leaves starting from 4 to 45 weeks after emergence in the fields. A total of nine fungicides with a control (only water spray) were evaluated in field conditions by foliar spray treatment. During *Kharif* 2016, the minimum disease intensity was recorded in propiconazole 25 EC (48.33%), followed by tebuconazole 25 WG (49.07%) and hexaconazole (50.19%), which are statistically at par (Table 2). In 2017, propiconazole 25 EC was found to be the best with a minimum disease intensity (28.44%), followed by hexaconazole 5 EC (30.56%), and mancozeb 75 WP (31.11%) stood at par. In 2018, minimum disease intensity was observed in treatment with propiconazole 25 EC (36.59%), tebuconazole 25 WG (38.66%), and mancozeb 75 WP (38.96%), and it was at par. In pool observation, the minimum leaf spot disease intensity was observed in propiconazole 25 EC (37.80%), followed by mancozeb 75 WP (40.27%), hexaconazole (40.60%), tebuconazole 25 WG (40.99%), difenoconazole (41.67%), and carbendazim 12% + mancozeb 63% WP (41.69%), which are statistically at par (Table 2). Further, analysis of the AUDPC (Area Under Disease Progress Curve) value revealed mancozeb 75 WP alone (1202.78) and in combination with carbendazim 50 WP (1215.28) was found to be best to reduce disease progress, followed by propiconazole 25 EC (1223.61) during 2016. In 2017, minimum AUDPC was observed in treatment with propiconazole 25 EC treatment (892.61), followed by hexaconazole (946.31). In 2018, minimum AUDPC was recorded in propiconazole 25 EC (1379.20) (Table 2). In pool observation, minimum AUDPC was observed (Table 2) in propiconazole 25 EC (1165.14), followed by mancozeb 75 WP (1225.83), carbendazim 12% + mancozeb 63% WP (1248.51), tebuconazole 25 WG (1253.01), and hexaconazole (1255.04), which are statistically at par.

Table 2. Effect of fungicidal sprays on Alternaria leaf blight disease intensity and disease progress in groundnut.

Sr. No.	Treatments	Percent Disease Intensity				AUDPC			
		2016	2017	2018	Pooled	2016	2017	2018	Pooled
1.	Difenoconazole 25 EC	50.74 (45.69 ^{bcd})	33.98 (35.92 ^{abc})	40.29 (39.67 ^{ab})	41.67 (40.43 ^{bc})	1256.94 ^{b}	1046.77 ^{bcd}	1540.60 ^{abc}	1281.44 ^{bc}
2.	Hexaconazole 5 EC	50.19 (45.38 ^{cd})	30.56 (33.82 ^{de})	41.03 (40.11 ^{ab})	40.60 (39.77 ^{bc})	1248.61 ^{b}	946.31 ^{de}	1570.20 ^{abc}	1255.04 ^{bcd}
3.	Propiconazole 25 EC	48.33 (44.31 ^{d})	28.44 (32.47 ^{e})	36.59 (37.50 ^{b})	37.80 (38.09 ^{c})	1223.61 ^{b}	892.61 ^{e}	1379.20 ^{c}	1165.14 ^{d}
4.	Tebuconazole 25 WG	49.07 (44.74 ^{cd})	35.22 (36.67 ^{ab})	38.66 (38.70 ^{b})	40.99 (40.03 ^{bc})	1226.39 ^{b}	1094.28 ^{ab}	1438.37 ^{bc}	1253.01 ^{bcd}
5.	Carbendazim 50 WP	52.96 (46.96 ^{b})	34.15 (36.03 ^{abc})	40.88 (40.01 ^{ab})	42.67 (41.00 ^{ab})	1305.56 ^{b}	1023.65 ^{bcd}	1656.20 ^{ab}	1328.47 ^{b}
6.	Mancozeb 75 WP	50.74 (45.69 ^{bcd})	31.11 (34.17 ^{cde})	38.96 (38.85 ^{b})	40.27 (39.57 ^{bc})	1202.78 ^{b}	971.06 ^{cde}	1503.67 ^{bc}	1225.83 ^{cd}
7.	Metiram 70 WG	51.11 (45.90 ^{bc})	33.07 (35.38 ^{bcd})	42.07 (40.71 ^{ab})	42.08 (40.67 ^{b})	1233.33 ^{b}	1078.18 ^{abc}	1656.20 ^{ab}	1322.57 ^{b}
8.	Pyraclostrobin 133 g/L + Epoxiconaxole 50 g/L SE	51.11 (45.90 ^{bc})	35.26 (36.68 ^{ab})	40.29 (39.67 ^{ab})	42.22 (40.75 ^{b})	1231.94 ^{b}	1117.00 ^{ab}	1625.00 ^{ab}	1324.65 ^{b}
9.	Carbendazim 12% + Mancozeb 63% WP	50.56 (45.59 ^{bcd})	35.62 (33.48 ^{bcd})	41.03 (40.10 ^{ab})	41.69 (40.43 ^{bc})	1215.28 ^{b}	1005.99 ^{bcd}	1524.27 ^{abc}	1248.51 ^{bcd}
10.	Control (Water spray)	58.15 (49.97 ^{a})	37.18 (37.85 ^{a})	45.33 (42.59 ^{a})	46.89 (43.47 ^{a})	1440.28 ^{a}	1194.67 ^{a}	1753.90 ^{a}	1457.95 ^{a}
	SE.M. ±	0.45	0.63	1.09	0.449	33.86	35.08	68.70	29.09
	C.D. at 5%	1.35	1.88	NS	1.27	100.60	104.23	204.14	82.01
	Y xT	-	-	-	NS	-	-	-	NS
	C.V.%	1.71	3.09	4.76	3.32	4.66	5.87	7.61	6.55

Note: Values in parentheses are arcsine-transformed values; treatment means with the common letter/letters are not significant by DNMRT at the 5% level. NS represents non-significant difference between treatment means.

3.3. Effect of Fungicides on Groundnut Yield

A similar trend was reflected in pod and haulm yield. The highest pod yield (1086 kg/ha and 3111 kg/ha) and haulm yield (1629 kg/ha and 5116 kg/ha) were recorded in propiconazole 25 EC during 2017 and 2018, respectively, followed by tebuconazole 25 WG with pod yields of 892 kg/ha and 3094 kg/ha and haulm yields of 1338 kg/ha and 4884 kg/ha during 2017 and 2018, respectively. But, in 2016, non-significant yield differences among treatments were observed, with the highest pod and haulm yield recorded in the carbendazim 50 WP treated plot (3021 kg/ha and 4834 kg/ha), followed by tebuconazole 25 WG (2803 kg/ha and 4485 kg/ha) (Table 3), while the combination of carbendazim 12% + mancozeb 63% WP ranked third with 2729 kg/ha and 4366 kg/ha, respectively. In the pool observation, the maximum pod yield and haulm yield were observed in tebuconazole 25 WG (2263 kg/ha and 3569 kg/ha), followed by propiconazole 25 EC (2207 kg/ha and 3541 kg/ha) (Table 3). Along with these, carbendazim 50 WP (2082 kg/ha and 3458 kg/ha), mancozeb 75 WP (2071 kg/ha and 3331 kg/ha), carbendazim 12% + mancozeb 63% WP (2029 kg/ha and 3372 kg/ha), and hexaconazole (2005 kg/ha and 3335 kg/ha) were also effective to obtain better pod and haulm yield.

Table 3. Effect of fungicidal sprays on pod yield and haulm yield of groundnut against Alternaria leaf blight.

Sr. No.	Treatments	Pod Yield (Kg/ha)				Haulm Yield (Kg/ha)			
		2016	2017 *	2018	Pooled	2016	2017	2018	Pooled
1.	Difenoconazole 25 EC	2619 ^{a}	842 ^{ab}	2226 ^{bc}	1896 ^{ab}	4190 ^{ab}	1263 ^{bc}	4028 ^{abc}	3160 ^{ab}
2.	Hexaconazole 5 EC	2721 ^{a}	913 ^{ab}	2382 ^{abc}	2005 ^{a}	4354 ^{ab}	1370 ^{b}	4282 ^{b}	3335 ^{ab}
3.	Propiconazole 25 EC	2423 ^{a}	1086 ^{a}	3111 ^{a}	2207 ^{a}	3877 ^{b}	1629 ^{a}	5116 ^{a}	3541 ^{a}
4.	Tebuconazole 25 WG	2803 ^{a}	892 ^{ab}	3094 ^{a}	2263 ^{a}	4485 ^{ab}	1338 ^{b}	4884 ^{b}	3569 ^{a}
5.	Carbendazim 50 WP	3021 ^{a}	854 ^{ab}	2372 ^{abc}	2082 ^{a}	4834 ^{a}	1281 ^{bc}	4259 ^{bc}	3458 ^{a}
6.	Mancozeb 75 WP	2537 ^{a}	854 ^{ab}	2823 ^{ab}	2071 ^{a}	4059 ^{b}	1282 ^{bc}	4653 ^{bc}	3331 ^{ab}
7.	Metiram 70 WG	2511 ^{a}	784 ^{b}	2365 ^{abc}	1887 ^{ab}	4018 ^{b}	1176 ^{c}	3565 ^{c}	2920 ^{ab}
8.	Pyraclostrobin 133 g/L + Epoxiconaxole 50 g/L SE	2585 ^{a}	860 ^{ab}	2063 ^{bc}	1835 ^{ab}	4136 ^{ab}	1291 ^{bc}	4005 ^{bc}	3144 ^{ab}
9.	Carbendazim 12% + Mancozeb 63% WP	2729 ^{a}	762 ^{b}	2597 ^{ab}	2029 ^{a}	4366 ^{ab}	1143 ^{c}	4606 ^{c}	3372 ^{a}
10.	Control (No spray)	2337 ^{a}	641 ^{b}	1722 ^{c}	1567 ^{b}	3739 ^{b}	961 ^{d}	3079 ^{d}	2593 ^{b}
	SE.M. ±	297.26	82.17	241.57	134.494	220.61	46.63	341.32	236.18
	C.D. at 5%	NS	NS	717.76	379.07	NS	138.54	1041.14	669.68
	Y xT				NS	-	-	-	NS
	C.V.%	19.59	16.77	16.90	19.74	9.10	6.34	13.92	12.62

Note: Treatment means with common a letter/letters are not significantly different from each other by DNMRT at the 5% level of significance. * In 2017, the plant population was reduced significantly due to *Aspergillus* collar rot. Here, the effect of years on the treatment mean is non-significant (NS).

3.4. Effect of Fungicides on Plant Growth and Chlorophyll

Different vegetative growth parameters, such as plant height and root length of groundnut, differed significantly as a consequence of the foliar spray of fungicides. The maximum plant height was observed in the propiconazole spray plot (39.55 cm), which is at par with the tebuconazole spray plot (37.10 cm); this was followed by spraying with carbendazim 12% + mancozeb 63% WP, carbendazim 50 WP, pyraclostrobin 133 g/L +epoxiconaxole 50 g/L SE, and hexaconazole 5 EC (Figure 3A). Whereas, minimum plant height was recorded in the control plot (without fungicide spray). A similar trend was observed in the root length also. The maximum root length was recorded in plants treated with propiconazole 25 EC (17.70 cm), tebuconazole 25 WG (17.11 cm), and difenoconazole 25 EC (16.81 cm) (Figure 3B). This is followed by plants sprayed with hexaconazole 5 EC, carbendazim 50 W, and carbendazim 12% + mancozeb 63% WP. The lowest observation was recorded in the untreated plot.

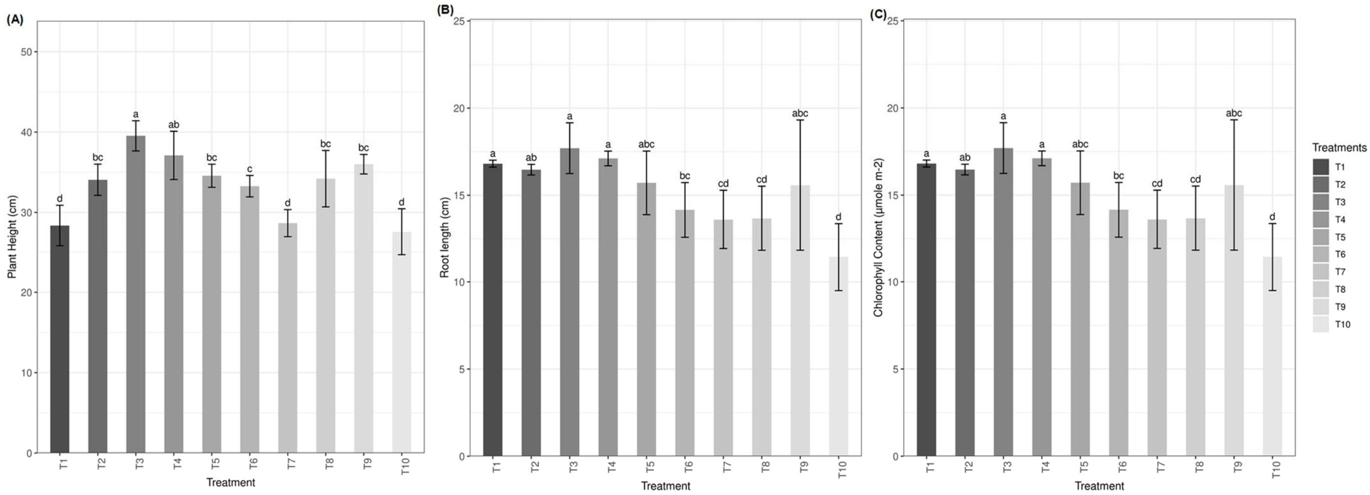

Figure 3. Effect of fungicide treatments on plant growth during 2018. The significant difference in the plant height (**A**), root length (**B**), and chlorophyll content (**C**) was recorded. The highest plant growth with maximum chlorophyll content was recorded in propiconazole 25 EC treatment (T3). Where T1 (difenoconazole 25 EC), T2 (hexaconazole 5 EC), T3 (propiconazole 25 EC), T4 (tebuconazole 25 WG), T5 (carbendazim 50 WP), T6 (mancozeb 75 WP), T7 (metiram 70 WG), T8 (pyraclostrobin 133 g/L + epoxiconaxole 50 g/L SE), T9 (carbendazim 12% + mancozeb 63% WP), and T10 (untreated control) represent different fungicide treatments sprayed in the field. The bar representing the values of treatment means with common a letter/letters are not significantly different from each other by DNMRT at the 5% level of significance.

The chlorophyll content in groundnut was also influenced by fungicide spray. The maximum chlorophyll content in the leaves was observed in plants treated with propiconazole 25 EC (95.06 µmole m^{-2}), which was significantly higher than other treatments (Figure 3C). This is followed by tebuconazole 25 WG (86.90 µmole m^{-2}), carbendazim 12% + mancozeb 63% WP (81.83 µmole m^{-2}), and hexaconazole 5 EC (81.56 µmole m^{-2}) treated plots. The lowest chlorophyll content was recorded in the fungicide-untreated plots. The average chlorophyll content of groundnut plants was estimated at the pod-filling stage; the significant difference in the chlorophyll content of the various treatments signifies its importance in relation to variance in plant growth.

3.5. Correlation Matrix Between Disease Severity, Yield, and Growth Parameters

The correlation matrix (Table S1) revealed significant associations between disease severity and various growth and yield parameters in groundnut. Disease severity exhibited strong and significant negative correlations with pod yield (r = −0.823, $p < 0.01$), haulm yield (r = −0.798, $p < 0.01$), plant height (r = −0.701, $p < 0.05$), root length (r = −0.779, $p < 0.01$), and chlorophyll content (r = −0.833, $p < 0.01$). Whereas, pod yield and haulm yield showed highly significant and positive correlations with plant height (r = 0.817, $p < 0.01$; r = 0.865, $p < 0.01$), root length (r = 0.822, $p < 0.01$; r = 0.852, $p < 0.01$), and chlorophyll content (r = 0.872, $p < 0.001$; r = 0.904, $p < 0.001$), but negatively correlated with disease severity. Overall, the reduced disease severity is associated with improved plant growth, higher chlorophyll content, and increased pod and haulm yields (Figure 4).

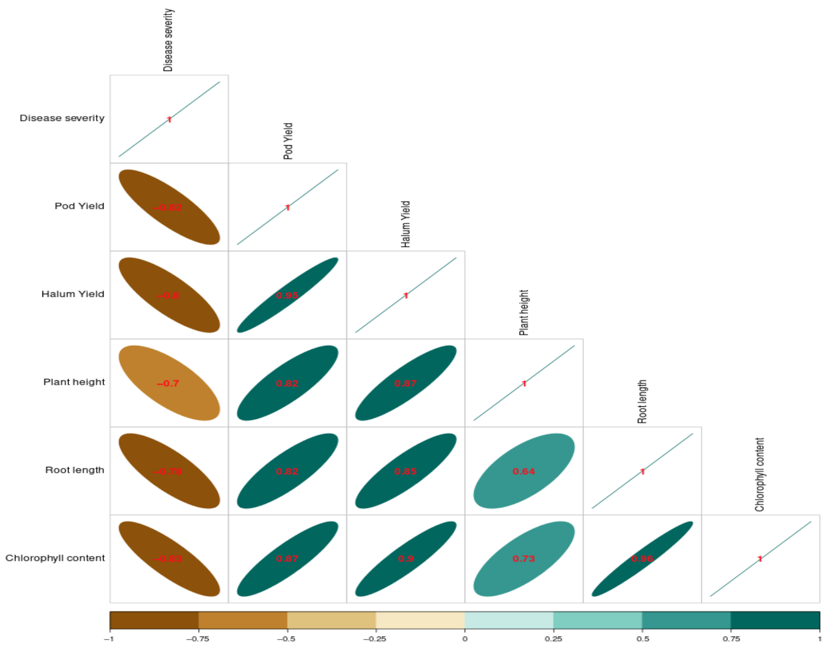

Figure 4. Correlogram showing pairwise correlation coefficients among disease severity, pod yield, haulm yield, plant height, root length, and chlorophyll content in groundnut. Positive correlations are indicated in green and negative correlations in red, with color intensity and circle size proportional to the correlation strength. Significance levels are denoted as $p < 0.05$.

3.6. Economics of the Fungicide Spray

Minimum disease intensity and AUDPC with higher pod and haulm yield were recorded in propiconazole 25 EC treatment. The data showed that maximum net realization and gain were obtained in tebuconazole 25 WG, followed by propiconazole 25 EC. But the highest incremental cost–benefit ratio (ICBR) was obtained in carbendazim 50 WP (1:11.31) followed by propiconazole 25 EC (1: 9.11) and tebuconazole 25 WG (1:6.18) (Table 4). Thus, a prophylactic spray of carbendazim 50 WP followed by two need-based sprays of propiconazole 25 EC and tebuconazole 25 WG was found most effective in terms of disease management and obtaining better yield.

Table 4. Details of incremental cost–benefit ratio (ICBR) for different treatments.

Sr. No.	Treatments	Qty of Treatment (kg/L per ha)	Price of the Treatment (Rs./ha)	Labor Cost (Rs/ha)	Total Cost of Treatment (Rs/ha)	Yield (Kg/ha)		Gross Realization (Rs/ha)	Net Realization over Control (Rs/ha)	Net Gain (Rs/ha)	ICBR
						Pod	Haulm				
1.	Difenoconazole 25 EC	1.500	6000	924	6924	1896	3160	85,320	14,861	7937	1:1.15
2.	Hexaconazole 5 EC	4.500	3240	924	4164	2005	3335	90,205	19,746	15,582	1:3.74
3.	Propiconazole 25 EC	1.500	1890	924	2814	2207	3541	98,903	28,444	25,630	1:9.11
4.	Tebuconazole 25 WG	1.500	3360	924	4284	2263	3569	101,227	30,768	26,484	1:6.18
5.	Carbendazim 50 WP	1.500	960	924	1884	2082	3458	93,654	23,195	21,311	1:11.31
6.	Mancozeb 75 WP	4.500	2250	924	3174	2071	3331	92,833	22,374	19,200	1:6.05
7.	Metiram 70 WG	6.000	5850	924	6774	1887	2920	84,240	13,781	7007	1:1.03
8.	Pyraclostrobin 133 g/L + Epoxiconaxole 50 g/L SE	1.875	4375	924	5299	1835	3144	82,832	12,373	7074	1:1.33
9.	Carbendazim 12%+ Mancozeb 63% WP	1.500	1680	924	2604	2029	3372	91,276	20,817	18,213	1:6.99
10.	Control (No spray)	-	-	-	-	1567	2593	70,459	-	-	-

Note:

Product	Cost	Product	Cost	Product	Cost
Difenoconazole 25 EC	Rs.1000/250 ml	Propiconazole 25 EC	Rs.630/500 mL	Carbendazim 12% + Mancozeb 63% WP	Rs.280/250 gm
Hexaconazole 5 EC	Rs.180/250 ml	Tebuconazole 25 WG	Rs.1120/500 mL	Pyraclostrobin 133 g/L + Epoxiconaxole 50 g/L SE	Rs.700/300 mL
Metiram 70 WG	Rs.390/400 gm	Carbendazim 50 WP	Rs.320/500 gm	Groundnut pod	Rs.40/kg
Mancozeb 75 WP	Rs.250/500 gm	Groundnut haulm	Rs.3/kg	Labor charges	Rs.308/day

4. Discussion

Alternaria leaf blight is an emerging disease in groundnut. It is widespread in major groundnut-growing areas of India, especially Gujarat [3], Maharastra [20], etc. The disease becomes havoc during the rainy season, primarily because of the warm–humid situation in different groundnut growing areas, resulting in 13–22% yield loss [3]. The pathogen was identified as *A. alternata*, which is responsible for foliar diseases in different crops like cotton [21], cumin [22], sesame [23], sunflower [24], etc., and poses significant challenges to agricultural productivity. The increasing prevalence of ALB in different crops is attributed to the changing climate conditions, and farmers are struggling to find suitable solutions. Despite various environmental challenges, many farmers still rely on chemical fungicides to control ALB. Thus, in the present study, the bioefficacy of different fungicides was tested to combat ALB in groundnut.

In our field experiment, it was observed that propiconazole 25 EC, tebuconazole 25 WG, carbendazim 12% + mancozeb 63% WP, and manzozeb 75 WP are the best fungicides for managing Alternaria leaf spots and obtaining higher pod and haulm yield in groundnut with higher economic benefits. These fungicides can be effective when applied as part of a regular spray schedule. Previously, mancozeb at 0.2% was identified as the best in minimizing the foliar disease intensity (22.95%) in groundnut with maximum pod (1873 kg ha^{-1}) and haulm (4648 kg/ha) yield in the field condition [25]. Similarly, Nath et al. [26] reported mancozeb (0.25%) and tebuconazole (0.1%) as the most effective fungicides against the leaf spot pathogen (*C. personatum*) of groundnut. This is also supported by Mushrif et al. [27], who reported tebuconazole (0.1%) as the most effective against leaf spots in groundnuts. Further, carbendazim 12% + mancozeb 63% WP was also identified as the best in obtaining that maximum pod yield in groundnut [28]. Interestingly, the bioefficacy of propiconazole was evaluated against Cercospora leaf spot in groundnut by various scientists either as a solo [29] or ready-mix fungicide [30,31]. Still, less information was available against Alternaria leaf blight in groundnut. Only in our investigation was propiconazole found to work best against Alternaria leaf blight in groundnut. Although, propiconazole was previously found effective against Alternaria leaf blight in chrysanthemum [32], sunflower [33], cowpea [34], etc. As disease severity has been negatively correlated with yield, the fungicidal treatment of propiconazole 25 EC and tebuconazole 25 WG significantly reduced the yield loss and increased the plant height, haulm weight, chlorophyll content, etc.

Previously, the plant growth retardant function of different triazole compounds, viz., propiconazole, tebuconazole, and hexaconazole, was reported [35]. They were found to affect hormonal balance, enzyme activity, lipid peroxidation, biomass, and yield in various crops [36] via targeting cytochrome P450-mediated oxidative demethylation, gibberellin, abscisic acid, and brassinosteroid biosynthesis pathways [37,38]; especially when multiple applications performed at the higher dose [39]. In our research, we explored the beneficial effect of propiconazole and tebuconazole on the stem and root growth of groundnut. This is corroborated with previous studies on *Catharanthus roseus* [40], tomato [41], and green gram [42]. Triazole compounds promote plant growth (shoot and root length) by balancing the auxin and cytokinin concentration [43] via counteracting gibberellin biosynthesis [44]. Furthermore, increased plant biomass was also recorded with propiconazole and tebuconazole treatment. Previously, the triazole fungicide application was reported to increase plant biomass of *Mentha piperita* [45]. Similarly, enhanced fresh weight, dry weight, and plant biomass of *Daucus carota* by hexaconazole treatment were observed [46,47]. However, no significant variation in chlorophyll content was observed in hexaconazole-treated carrot plants. Interestingly, the beneficial impact of propiconazole on the green leaf color with higher photosynthetic pigment (chlorophyll) content in groundnut was observed compared to other treatments. The potential role of propiconazole in synthesizing more chlorophyll helped in delaying leaf senescence. A similar impact of propiconazole was observed in sorghum [48]. The triazole-induced activity of cytokinin stimulates chlorophyll biosynthesis in plants [49], which in turn increases the activity of antioxidant-scavenging enzymes [50,51], thus enhancing various stress tolerances in many plants. Thus, besides fungitoxic activity, triazoles, especially propiconazole and tebuconazole, can be employed as potential plant growth promoters in groundnut.

Alternaria species are known for their high genetic diversity and adaptability [52], which makes them prone to developing fungicide resistance, especially under continuous selection pressure. The repeated and indiscriminate use of single-site fungicides, such as demethylation inhibitors (DMIs/triazoles), quinone outside inhibitors (QoIs/strobilurins), or succinate dehydrogenase inhibitors (SDHIs), can exert strong selection pressure on pathogen population and leads to the emergence of fungicide-resistant isolates [53]. Once resistance emerges, it often persists due to the stable inheritance of resistant traits, leading to reduced field performance of the selective fungicides. Cross-resistance within the same mode-of-action group further limits fungicide options [54]. In Alternaria, reduced sensitivity to QoIs and DMIs has already been reported in several crops worldwide [55], indicating that similar risks exist for any crop–pathogen system, including groundnut. Therefore, adopting an integrated disease management strategy combining cultural practices and resistant varieties along with judicious use of fungicides, such as rotating fungicides with different FRAC codes, limiting the number of applications per season, etc. is essential for prolonging the effectiveness of available fungicides in managing Alternaria blight in groundnut. Here, managing ALB in groundnut effectively often involves the scheduled application of fungicides having plant growth promotion and disease suppression ability. But the development of fungicide resistance in pathogen populations is a major concern; thus, alternate application of different systemic fungicides, viz., propiconazole 25 EC and tebuconazole 25 WG, or spraying of combi-fungicides, viz., carbendazim 12%+mancozeb 63% WP, would be the best choice. Therefore, scheduled-based application of these fungicides is a prerequisite for better efficacy.

5. Conclusions

Groundnut cultivation is significantly constrained by Alternaria leaf blight (ALB), which adversely affects both yield and seed quality. Timely application of fungicides is crucial to prevent severe disease outbreaks and minimize yield losses. Based on multi-season field evaluations, propiconazole 25 EC, tebuconazole 25 WG, and the combination fungicide carbendazim 12% + mancozeb 63% WP were identified as the most effective treatments for managing ALB and enhancing economic returns. Additionally, propiconazole 25 EC and tebuconazole 25 WG demonstrated notable growth-promoting effects on groundnut, contributing to improved plant vigor. Therefore, it is recommended to farmers to adopt an alternate spray schedule of propiconazole 25 EC (10 mL/10 L water), tebuconazole 25 WG (10 g/10 L water), and carbendazim 12% + mancozeb 63% WP beginning from the disease initiation, for the effective and economical management of Alternaria leaf blight in groundnut. The findings are based on trials in a specific agro-climatic region, and long-term fungicide resistance in *Alternaria* populations was not evaluated. Over-reliance on fungicides with single modes of action increases fungicide resistance risk in Alternaria populations. Therefore, an integrated management strategy combining cultural, chemical, biological, and host resistance measures is the most effective and environmentally sound approach. Adoption of such practices not only prolongs the efficacy of available fungicides but also ensures stable yields and long-term crop health. Further studies focusing on the molecular mechanisms of triazole-induced growth promotion and long-term resistance monitoring must be conducted for sustainable management options.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/crops5050060/s1, Table S1: Weather data of experimental site during crop growing period of 2016, 2017, and 2018.

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Abbreviations

The following abbreviations are used in this manuscript: Alternaria Leaf Blight (ALB), Area Under Disease Progress Curve (AUDPC), Deoxyribonucleic Acid (DON), Emulsifiable Concentrate (EC), Hectare (Ha), Potato Dextrose Agar (PDA), Suspension Emulsion (SE), Wettable Granule (WG), and Wettable Powder (WP).

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