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Integration of host resistance and fungicides reduced ascochyta blight pressure and minimised yield loss in field pea (*Pisum sativum* L.) in southern Ethiopia

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ABSTRACT
Ascochyta blight complex causes substantial yield losses and deteriorates seed quality of field pea worldwide. Field experiments were conducted to determine the effectiveness of an integrated approach consisting of host resistance and fungicides to reduce ascochyta blight progression and enhance yield performances of field pea for two seasons at Bonke and Chencha, Southern Ethiopia. Three field pea (Bursa, Burqitu and Tegegnech) varieties and three systemic (Carbonchlor, Matico and Othello-Top) fungicides, along with unsprayed controls, were arranged in a factorial randomised complete block design with three replications. Results showed that fungicide treated plots of each variety recorded the lowest progress rate, while control plots of Bursa, Burqitu and Tegegnech recorded the highest rate parameter (0.67, 0.60 and 0.451 units day^{-1}), respectively at Bonke. Terminal mean severities were reduced by up to 24.6–43.7% and 20.1–43.7% due to fungicide applications over unsprayed plots at Chencha and Bonke, respectively. Moreover, triple applications of Othello-Top enhanced grain yield by 211% (Bursa), 204% (Burqitu) and 140% (Tegegnech) as compared to control plots at Bonke. A related pattern was noticed at Chencha areas. Economically, Burqitu with Othello-Top showed the highest net benefit and benefit–cost ratio of \$2.35 × 10^{3} ha^{-1} and 4.77 (Bonke) and 2.27 × 10^{3} ha^{-1} and 3.76 (Chencha) in that order of presentation, followed by Matico, and found to be the most profitable management option due to monetary advantage; and it could be suggested for field pea growers.

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Disease progression; fungicide; integration; severity; variety; yield

Introduction

Field pea (*Pisum sativum* L.) is a major cool-season multipurpose crop, which is widely cultivated for grain and green pods in tropical, subtropical, and temperate regions of the world (Rana et al. 2013; FAOSTAT 2021). The crop is mainly produced for human food, animal feed, and as a source of income for producers (Azam et al. 2020; USDA 2022). It is an important source of proteins and other nutrients for the human diet (Kumari and Deka 2021). In addition, the crop is an essential component of sustainable cropping systems where it is used in nitrogen fixation for the advantage of crop rotations (Jensen et al. 2012; Tran 2017), and is effective in breaking disease cycles in some pathogens (Davidson and Kimber 2007).

Globally, more than 14.6 and 19.8 million tons of field pea were produced on around 7.19 and 2.33 million hectares of land as grains and green pods, respectively, in 2020 (FAOSTAT 2021). Canada (>14.48 million tons), Russia Federation (>1.67 million tons), France (>1.41 million tons), China (>1.34 million tons), and India (>797 thousand tons) are the leading pea-producing countries worldwide in 2020 (FAOSTAT 2021; USDA 2022). In this regard, Ethiopia ranked 10th in grain pea production with which around 268 thousand tons of grain yields were produced in 2020 (FAOSTAT 2021). The crop is widely produced in the highlands of Oromia, Amhara, Tigray, and Southern regional states (MoANR and EATA 2018). The crop is the third-largest highland pulse next to faba bean and chickpea in terms of household involvement, area coverage and total production in the country (CSA 2021). In southern Ethiopia, where this study was conducted, field pea has been cultivated on more than 62 thousand hectares of land and contributed more than 100 thousand tons of grain yields in the 2020/21 cropping season (CSA 2021).

However, the productivity of the crop is very low in the study areas (1.60 t ha^{-1}) as well as in Ethiopia

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(1.71 t ha^{-1}) (CSA 2021), which are below the agronomic potential of the crop, > 4.80 t ha^{-1} (Kedir et al. 2020) and even from the world average (2.03 t ha^{-1}) productivity (FAOSTAT 2021). Low productivity of field pea is associated with biotic and abiotic stresses, the inherent low-yielding potential of the local cultivars, socio-economic challenges, and poor agronomic field management (Davidson and Kimber 2007; MoANR and EATA 2018). Among biotic challenges, ascochyta blight caused by *Ascochyta* spp. is regarded as an economically important and a major constraint in field pea production in Ethiopia (MoANR and EATA 2018) and in worldwide agriculture (Bretag et al. 2006; Davidson and Kimber 2007; Tran 2017).

Ascochyta blight can infect all above-ground parts of the crop in all growth stages and is characterised by necrotic lesions leading to breakage of stem and defoliation of leaves resulting in severe yield reduction. In addition, it results in seed quality deterioration or retardation of seed development during the growing season (Panicker and Ramraj 2010; Assen 2020). Significant yield losses vary depending on crop growth stage, the susceptibility of the crop to environmental conditions and cropping systems (Garry et al. 1998; Česnulevičienė et al. 2014). Yield losses due to ascochyta blight are estimated at up to 50% in Canada (Xue et al. 1996b), 10–30% in China (Liu et al. 2016) and 15–100% in Australia (Bennett et al. 2019; Barbetti et al. 2021), and yield losses ranging from 25 to 70% had been reported under field conditions in Ethiopia (Tegegn and Teshome 2017; MoANR and EATA 2018). Also, the disease remains a serious threat to field pea production in the study areas, southern Ethiopia. Thus, to reduce losses due to the disease, effective management options should be warranted and forwarded for the farming communities to ensure pea production.

Several management strategies, such as crop rotations, use of clean and disease-free seeds and host resistance (Kimber et al. 2007; Davidson 2012; Tran 2017); delaying sowing date (Panicker and Ramraj 2010); deep plowing immediately after harvesting (Kraft et al. 1998); crop residue management (Bailey et al. 2001); avoiding planting under water-logged conditions (McDonald and Dean 1996); fungicide seed treatment (Bretag et al. 2006); and fungicide foliar application (Warkentin et al. 2000; Xue et al. 2003; Bretag et al. 2006; GRDC 2018; Walela et al. 2018) have been recommended worldwide. Likewise, management options for ascochyta blight of field pea mainly relied on the use of resistant varieties, and a few farmers and private investors practice fungicide applications, which have been registered for other crop diseases, in the study areas and other parts of Ethiopia (MoANR and EATA 2018).

Despite the fact, cultural practices could offer limited protection as such tactics only lower the amount of inocula found in the field and are highly influenced by several environmental conditions (Madden et al. 2007). Although host resistance is also the most cost-effective, efficient, eco-friendly and sustainable management option, it could not provide a year-round protection because of the vulnerability of the resistance genes due to continuous variability within the pathogen (Pande et al. 2005; Bretag et al. 2006; Davidson and Kimber 2007; Khan et al. 2013). More importantly, fungicide spray could render the most effective management option for ascochyta blight; however, recurrent and unwise use of fungicides resulted in the development of pathogen resistance and resurgences (Campbell and Madden 1990; Wise et al. 2008), and adverse effects on human health, non-target organisms and the environment (Mostafalou and Abdollahi 2012; Liu et al. 2016). Thus, Bretag et al. (2006), Davidson and Kimber (2007) and Gossen et al. (2011) suggested an integrated management option that combines the use of disease-free planting materials, elimination of sources of disease infection, following optimal planting time, choice of varieties with notable resistance, seed treatment, and fungicide spray that have a pronounced effect in reducing the damages of ascochyta blight in field pea cultivation.

But, research works have not been in place regarding the rational use of fungicides in an integrated approach with host resistance for ascochyta blight management in the study areas and the country as well. On the other hand, there are several pea varieties having different levels of resistance to ascochyta blight in the production systems of the country though they are significantly affected by ascochyta blight due to the loss of durability of the genes that confer resistance. Moreover, there are many fungicides which have been registered for different crop diseases in Ethiopia, not for ascochyta blight. As a result, attempts have been made by a few farmers and private investors to apply fungicides registered for potato and tomato diseases to control ascochyta blight. However, the efficacy of the fungicides may vary with the active ingredients, mode of application, time of application, spray frequency, and host and pathogen resistance; and the use of fungicides could also be compromised by health and environmental risks. To this end, an integrated use of host resistance and fungicide may help to reduce the risks of sole use of fungicide as well as early breaking down of resistance genes of the host, thereby reducing damages in agronomic traits of the crop. Therefore, the study was conducted with the objective to evaluate the effectiveness of the combined use of host resistance and fungicide foliar spray to reduce ascochyta blight intensity and yield losses and enhance the agronomic performances of field pea in Southern Ethiopia.

Materials and methods

Overview of experimental areas

The experiments to determine the effectiveness of an integrated approach consisting of host resistance and fungicide application to reduce ascochyta blight development and enhance yield performances field pea varieties were conducted at farmer's fields of Bonke and Chencha, Southern Ethiopia, during the 2020 and 2021 main cropping seasons. Experimental areas were selected based on production potential and being hot spots for ascochyta blight epidemics during each cropping year. At Bonke, the study site is located at 6° 4′53.472″ N and 37°18′33.696″ E geographic coordinates with an altitude of 2651 m above sea level (m a.s.l). At Chencha, the study site is found at 6°16′23.196″ N and 37°35′29.976″ E and at an altitude of 2668 m a.s.l. Weather data for the two cropping seasons are summarised in Table 1.

Treatments, design and field establishment

In this study, three field pea varieties and three systemic fungicides were evaluated at each experimental site in the two cropping seasons. Field pea varieties that exhibit different levels of resistance to ascochyta blight, Bursa (resistant), Burqitu (moderately resistant) and Tegegnech (susceptible) were obtained from Holetta Agricultural Research Center, Ethiopian. The fungicides included Carbonchlor 50% SC [Carbendazim 25% + Chlorothalonil 25%], Matico [Metalaxyl 8% + Mancozeb 64% WP] and Othello-Top™ 350 SC [Azoyxstrobin 200 g/L + Difenoconazole 125 g/L]. The fungicides were collected from agro-chemical dealers, such as Hamlin Trading plc, Markos plc and Syngenta Agroservices – Ethiopia. Carbonchlor and Matico have systemic translocate and protectant mode action, while Othello-Top has systemic translaminar and protectant mode of action. Twelve treatment combinations, including unsprayed controls for each variety, were factorial arranged in a randomised complete block design with three replications.

At both locations in each season, a total field size of 14 m in width × 47.7 m in length was used. Each experimental plot and parallel replicas were spaced at 1.5 and 2.5 m, respectively. Seeds (= 52 plants per plot) were sown in 15 rows on a unit plot size of 2.6 m in length × 3.0 m in width, where 20 and 0.5 m were used between rows and plants, respectively. Sowing was performed on 20 and 15 July (at Bonke) and 20 and 23 July (at Chencha) in 2020 and 2021 in that order. Recommended NPS blended fertiliser (121 kg ha^{-1}) was uniformly applied at the time of sowing for each location as suggested by MoANR and EATA (2018). Fungicide application was done based on the manufacturer's spray rates and frequencies for each fungicide at 15 days interval. Fungicide rates of 2.5 L ha^{-1}, 3 kg ha^{-1}, and 1 L ha^{-1} with a dilution water volume of 1000, 800 and 250 L were used for Carbonchlor, Matico and Othello-Top, respectively.

Spraying was started when the first disease symptoms were observed on the susceptible variety (Tegegnech) at both locations in the two cropping years [i.e. at 6–8 node stage (5–6 true leaf stage)]. Accordingly, the first fungicide application was made at 40 (2020) and 37 (2021) days after sowing (DAS) at Bonke and 38 (2020) and 41 (2021) DAS at Chencha areas. A manual knapsack sprayer calibrated to deliver 500–700 L of water ha^{-1} was used for spraying. Three consecutive sprays for each fungicide were accomplished per plot at both locations over seasons. For each field pea variety, an unsprayed plot was left as a control for high ascochyta blight development to compare treatment effects. All other recommended agronomic practices were uniformly used as deemed necessary during the experimental periods.

Table 1. Total rainfall (mm), mean monthly minimum and maximum temperatures (°C), and relative humidity (%) for Bonke and Chencha areas, southern Ethiopia, during the two cropping seasons.

	Cropping months						
Weather variables[a]	June	July	August	September	October	November	December
Bonke							
Tmax.	22.6	21.3	20.8	24.9	22.5	22.6	22.6
Tmin.	13.7	12.3	12.1	14.3	13.1	14.1	15.8
Total RF	59.0	103	181	180	149	70.9	15.2
RH	69.9	78.3	80.6	74.7	73.5	58.9	54.3
Chencha							
Tmax.	25.1	24.2	22.2	22.8	23.2	22.9	25.2
Tmin.	11.6	11.7	12.9	12.4	11.9	12.5	16.3
Total RF	113	134	157	101	75.3	94.1	3.8
RH	76.5	79.1	69.9	67.7	68.3	56.6	52.8

[a]Tmax: Maximum mean monthly temperature; Tmin: Minimum mean monthly temperature; RF: Rainfall; and RH: Relative humidity.

Ascochyta blight monitoring

Ascochyta blight severity was assessed at a weekly interval before each fungicide application, starting from 40 and 37 DAS at Bonke and 38 and 41 DAS at Chencha in 2020 and 2021, respectively. Twenty randomly selected and pre-tagged plants from the thirteen central rows of each plot were used for severity assessment. A total of nine disease severity assessments were made per location for each cropping season. Ascochyta severity was scored using a 0–6 rating scale (Roger and Tivoli 1996); where, 0 = no symptom; 1 = few flecks observed on a leaf; 2 = numerous flecks observed on a leaf; 3 = coalescing necrotic lesions covering < 25% leaf area; 4 = coalescing necrotic lesions covering 25–50% of the organ area necrotic; 5 = coalescing necrotic lesions covering 50–75% of the organ area necrotic; and 6 = coalescing necrotic lesions covering 75–100% of the organ area necrotic. The severity scores were converted into percentage severity index (PSI) for analysis (Wheeler 1969).

$$\text{PSI} = \frac{\text{Sum of numerical ratings}}{\text{Number of plants scored} \times \text{maximum score on the scale}} \times 100$$

Area under disease progression curve, AUDPC (%-days), was computed from PSI values appraised at various days for each treatment combination using the following formula (Campbell and Madden 1990):

$$\text{AUDPC} = \sum_{i=1}^{n-1} \left(\frac{x_i + x_{i+1}}{2}\right)(t_{i+1} - t_i)$$

where x_i is the disease severity at the ith assessment, t_i is the time of the ith assessment in days from the first measurement date and n is the total number of disease assessments.

The two epidemiological models, Logistic ln[(y/1−y)] (van der Plank 1963) and Gompertz −ln[−ln(y)] (Berger 1981), were compared for the goodness of fitness for estimation of rates of disease progression from each treatment. The logistic model exhibited higher values of coefficient of determination (R^2) and lower standard error than the Gompertz model. Thus, the logistic epidemiological model [ln(y/1−y)] was chosen and employed to estimate the disease progress rate from the linear regression of transformed disease severity data versus days after sowing for each treatment using the following formula (van der Plank 1963):

$$y_t = \frac{1}{1 + \exp^{-\ln\left[\frac{yo}{1-yo}\right] + r_L t}}$$

where y_t is the percentage of severity at the tth assessment date; y_o is the percentage of initial severity at the tth assessment date; t_i is the time of the ith assessment in days from the first assessment date; and r_L is the rate parameter determined by the production of inoculum by infected individuals/lesions per unit area of diseased tissue.

Agronomic parameters and yield loss assessment

Agronomic parameters including plant height (PH), stand count (SC), number of productive pods per plant (NPP), number of seeds per pod (NSPP), hundred seed weight (HSW), and grain yield were recorded during the study. Plant height (cm) was measured at 90% days to physiological maturity from the central rows of randomly taken 10 plants per plot. Stand count at 90% days to physiological maturity was determined as a stand of plants within the 13 central rows of each plot. The NPP was assessed by counting the total number of pods of sample plants, while NSPP was recorded by counting the total number of seeds per pod from randomly taken 20 pods of 20 sample plants per plot. Mean values of each parameter were used for data analysis.

Grain yield was harvested at 154 and 150 (at Bonke) and 150 and 160 (at Chencha) days after sowing in the 2020 and 2021 cropping seasons, respectively. Grains were determined from the 13 harvestable central rows per plot (kg ha^{-1}). Grain yield was adjusted to 12% storable moisture content of grains of pulse crops using the procedure suggested by Taran et al. (1998). Moreover, hundred seed weight was recorded from grains randomly sampled per plot at harvest, and adjusted at 12% grain moisture content. Furthermore, yield losses were assessed to examine the effects of ascochyta blight on the performance of field pea varieties evaluated in the study. Thus, relative yield loss for each treatment was determined as percentage yield reduction of less protected plots as compared to maximum protected plots per location over years using the formula:

$$\text{Relative yield loss(\%)} = \frac{Y_{bt} - Y_{lt}}{Y_{bt}} \times 100$$

where Y_{bt} is the mean yield of the best performing treatment combination in the study (maximum protected plot) and Y_{lt} is the mean yield of the other treatments (low to medium protected plots).

Data analyses

Disease and agronomic data were subjected to analysis of variance (ANOVA) using the general linear model of

SAS version 9.3 (SAS 2014). If there were significant variations among the treatments, mean separation was employed using Fisher's protected least significant difference (LSD) test at 5% significance level. The two locations were considered as different environments and separate data analysis was employed for each location due to heterogeneity of error variances based on Bartlett's test. However, because of homogeneity in error variances for the study parameters within each location in the two years, combined data analysis of variance was done for both cropping seasons (Gomez and Gomez 1984). The association between AUDPC and grain yield was studied for yield loss prediction using linear regression analysis, as an integral yield loss assessment model. It was appraised using Minitab® (Release 15.0 for windows® 2007).

Economic feasibility analysis

Based on the pooled data from the two seasons for each location, an economic feasibility analysis for integrated ascochyta blight management alternatives was done using a partial budget analysis procedure developed by CIMMYT (1988). In this study, the net benefit and benefit–cost ratio were considered. The net benefit was determined as the difference between the gross benefit (products of market price and grain yield) and the total variable cost (expenses of fungicide, knapsack sprayer, and operating labour cost for application). The benefit–cost ratio was computed as the ratio of net benefit and total input costs. Partial budget analysis was employed based on the actual cost of fungicide, labour, and market price of grain yield in each location per season. Mean unit price of grain yield per kg during the 2020 (0.81 and 0.91 $) and 2021 (0.72 and 0.80 $) cropping years were 0.76 and 0.85 $ [at the exchange rate of 1$ = ETB 39.4 (2020) and 49.9 (2021)] at the time of marketing at Bonke and Chencha, respectively. The actual grain yield was adjusted downward by 10% to estimate the difference between the empirical and the farmers' grain yield expected from the same treatment. All costs were converted into hectare-basis for the proposed analysis.

Results

Disease severity (%)

Typical disease symptoms of ascochyta blight were noticed 40 and 37 days after sowing (DAS) at Bonke in 2020 and 2021, respectively. On the other hand, disease onset was recorded at 38 DAS (2020) and 41 DAS (2021) at Chencha areas. Interaction effects of field pea varieties × fungicides highly and significantly ($P < 0.0001$) influenced disease severity (consistently starting from the third date of assessment) at both locations (Table 2). At Bonke, the highest terminal means of disease severity of 47.0, 52.3 and 55.9% were recorded from untreated plots of Bursa, Burqitu and Tegegnech in that order of appearance. Conversely, fungicide treated plots of each field pea variety scored for the lowest final mean disease severity, which ranged from 27.6 to 32.9% in both years (Table 2). Amongst the fungicides, Othello-Top spraying resulted in terminal means severity reductions of 32.4 and 21.5% as compared to Carbonchlor and Matico applications on variety Bursa, respectively. Related trends were encountered for the other varieties at Bonke (Table 2).

Similarly, final mean severity that ranged from 21.8% to 39.0% for Bursa, 24.9% to 42.3% for Burqitu and 27.0% to 49.7% for Tegegnech were recorded at Chencha. However, control plots of Tegegnech recorded the highest (49.7%), while that of Bursa noticed relatively the lowest (39.0%) final mean severity. By applying fungicides, terminal mean severities could be reduced by 15.9–44.3% (Bursa), 19.5–41.2% (Burqitu) and 25.0–45.6% (Tegegnech) over unsprayed plots of each variety. Of which, Othello-Top application contributed to 44.3, 41.2 and 45.6% mean final severity reductions on Bursa, Burqitu and Tegegnech varieties as compared to control counterparts of each variety at Chencha, during the epidemic periods of the two years (Table 2). At both experimental locations, fungicide Matico performed better than Carbonchlor irrespective of field pea varieties in both years. The overall assessments showed that terminal mean disease pressure was relatively higher at Bonke (40.7%) than at Chencha (33.3%) in both seasons (Table 2).

Rate of ascochyta blight progression (r)

The apparent infection rate of ascochyta blight was determined to characterise disease progression as influenced by fungicide, host resistance and their combinations as variable factors. Hence, disease progress rates and parameter estimates of ascochyta blight are presented in Table 3. The overall analysis indicated that the mean rate of disease progression varied among varieties, fungicides and their combined applications at both locations. In this regard, higher progress rates were obtained from control plots of Bursa (0.67 units day^{-1}), Burqitu (0.60 units day^{-1}) and Tegegnech (0.45 units day^{-1}) than treated plots of each variety, which recorded only 0.29–0.61 units day^{-1} at Bonke. Among fungicide treated plots, Othello-Top and Matico applications reduced the progression rate of ascochyta

Table 2. Interaction effects of variety × fungicide application on ascochyta blight severity (%) of field pea at Bonke and Chencha, southern Ethiopia, during the 2020 and 2021 main cropping seasons.

Treatment combination		Disease severity (%), Bonke[1]			Disease severity (%), Chencha [1]		
Variety	Fungicide	PSI_7	PSI_8	PSI_9	PSI_7	PSI_8	PSI_9
Burqitu	Carbonchlor	35.9[de]	40.4[cd]	42.3[de]	25.6[cd]	28.4[de]	34.0[d]
	Matico	29.9[fg]	35.3[ef]	38.2[fg]	21.4[fg]	25.3[f]	30.7[ef]
	Othello-Top	23.6[hi]	28.8[hi]	31.0[ij]	16.3[hi]	19.7[h]	24.8[h]
	Unsprayed	44.7[b]	49.4[a]	52.3[b]	31.3[b]	34.1[b]	42.3[b]
Bursa	Carbonchlor	35.0[de]	38.2[de]	40.8[ef]	24.6[de]	26.6[ef]	32.8[de]
	Matico	27.1[gh]	32.8[fg]	35.1[gh]	18.8[gh]	22.2[g]	27.9[fg]
	Othello-Top	20.3[i]	25.6[i]	27.6[j]	13.9[i]	17.2[i]	21.7[i]
	Unsprayed	40.7[bc]	44.3[b]	47.0[c]	28.3[c]	30.9[c]	39.0[c]
Tegegnech	Carbonchlor	38.0[cd]	42.6[bc]	45.8[cd]	26.7[cd]	29.9[cd]	37.3[c]
	Matico	32.0[ef]	36.9[de]	39.5[ef]	22.1[ef]	26.2[ef]	31.9[de]
	Othello-Top	25.1[h]	30.9[gh]	32.9[hi]	17.4[gh]	21.3[gh]	27.0[gh]
	Unsprayed	49.8[a]	50.9[a]	55.9[a]	35.4[a]	40.9[a]	49.7[a]
Mean		33.5	38.0	40.70	23.5	26.9	33.3
CV (%)		10.7	8.25	7.63	10.6	7.18	7.39
P value		<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

[1]PSI_7–PSI_9 refers to percent severity index at the last-three dates of disease assessments at both experimental locations in the cropping years. CV: Coefficient of variation. Mean values in the same column with different letters represent significant variation at 5% probability level.

blight by 27.8–30.6% and 10.7–24.1% when compared with Carbonchlor spraying in that order of presentation at Bonke in 2020 and 2021 cropping years.

At Chencha areas, control plots of Burqitu recorded the highest (0.51 units day^{-1}) infection rate, followed by Bursa (0.49 units day^{-1}), while relatively the lowest progression was computed for control plots of Tegegnech (0.46 units day^{-1}). Comparatively, Othello-Top treated plots of Bursa (0.41 units day^{-1}), Burqitu (0.38 units day^{-1}) and Tegegnech (0.39 units day^{-1}) recorded the lowest apparent infection rate compared with Matico and Carbonchlor sprayed plots of each variety, which obtained 0.42–0.49 units day^{-1} of progress rate (Table 2). However, fungicide application lowered the state of ascochyta blight development by up to 25.6% as compared to control treatments. Though inconsistency was evident, the overall results indicated that the rate at which ascochyta blight progressed was relatively slow when fungicides were applied in integration with field pea varieties over that of untreated plots at both locations in both years (Table 3).

Disease progress curve

The most fundamental signature of summarising a plant disease epidemic, along with factors influencing it, is to plot disease levels at several times during the growing season. Hence, disease progress curves were developed using mean severity values of ascochyta blight and fungicide-treated and untreated classes of field pea genotypes to show the pattern of disease development over time and the effects of treatments on the epidemic (Figure 1(a,b)). Even though variable dates of disease onset had been recorded across locations over the two seasons, the disease progressed through each assessment date with a different rate of development. As demonstrated in the figure, treatments attained different disease progression in which the graph

Table 3. Disease progress rate (units day^{-1}) and parameter estimates of ascochyta blight of field pea under integrated management systems at Bonke and Chencha, Southern Ethiopia, during the 2020 and 2021 main cropping seasons.

Treatment combination		Disease progress rate (units day^{-1}), Bonke [a]				Disease progress rate (units day^{-1}), Chencha [a]			
Variety	Fungicide	Disease progress rate	SE of rate	SE of intercept	R^2 (%)	Disease progress rate	SE of rate	SE of intercept	R^2 (%)
Burqitu	Carbonchlor	0.534	0.091	0.512	83.0	0.473	0.059	0.335	90.0
	Matico	0.477	0.064	0.359	88.9	0.448	0.048	0.272	92.5
	Othello-Top	0.376	0.062	0.347	84.2	0.381	0.038	0.214	93.5
	Unsprayed	0.600	0.098	0.552	84.2	0.512	0.069	0.394	88.4
Bursa	Carbonchlor	0.615	0.096	0.537	85.6	0.492	0.064	0.361	90.3
	Matico	0.467	0.056	0.316	90.8	0.490	0.050	0.282	93.6
	Othello-Top	0.444	0.061	0.341	90.1	0.412	0.031	0.172	96.3
	Unsprayed	0.670	0.103	0.578	85.9	0.495	0.055	0.309	92.0
Tegegnech	Carbonchlor	0.419	0.054	0.304	89.6	0.453	0.065	0.365	88.8
	Matico	0.337	0.044	0.245	89.5	0.417	0.043	0.243	93.0
	Othello-Top	0.291	0.035	0.197	90.9	0.397	0.052	0.291	89.4
	Unsprayed	0.451	0.069	0.389	85.9	0.458	0.044	0.248	93.9

[a]Disease progress rate obtained from the regression line of disease severity against time of disease assessment. SE: Standard error of the rate and parameter estimates (intercept), and R^2 = Coefficient of determination for the Logistic epidemiological model.

tended to show that the disease rapidly increased in untreated plots during each assessment period with a high rate of development, irrespective of varieties compared. On the contrary, slow progression of ascochyta blight was observed when genotypes were treated with fungicides of different modes of action.

Ascochyta blight occurred 37–40 DAS and progressed up to 101–104 DAS, which was about 64 days of epidemic duration at Bonke areas in both years. Curves of Bursa, Burqitu and Tegegnech field pea varieties treated with fungicides initially seemed to increase, despite slight height variations, as untreated controls. That is, initial disease severity ranged from 0.77% to 3.06% and 0.61% to 2.96% for treated and control plots of field pea varieties, respectively at Bonke (Figure 2(a)). However, remarkable distinctions were evident among the response of field pea varieties to ascochyta blight pressure during the epidemic periods. Terminal mean severity of Bursa (34.5 and 47.0%), Burqitu (37.2 and 52.3%) and Tegegnech (39.4 and 55.9%) under fungicide application and control plots revealed the real disparities among the varieties in that order. After about the fifth and sixth dates of disease assessments, the rates of ascochyta blight development tended to stabilise and gradually declined thereafter in the epidemic periods at Bonke (Figure 1(a)). Similar trends of disease progress curves were also observed at Chencha areas (Figure 1(b)).

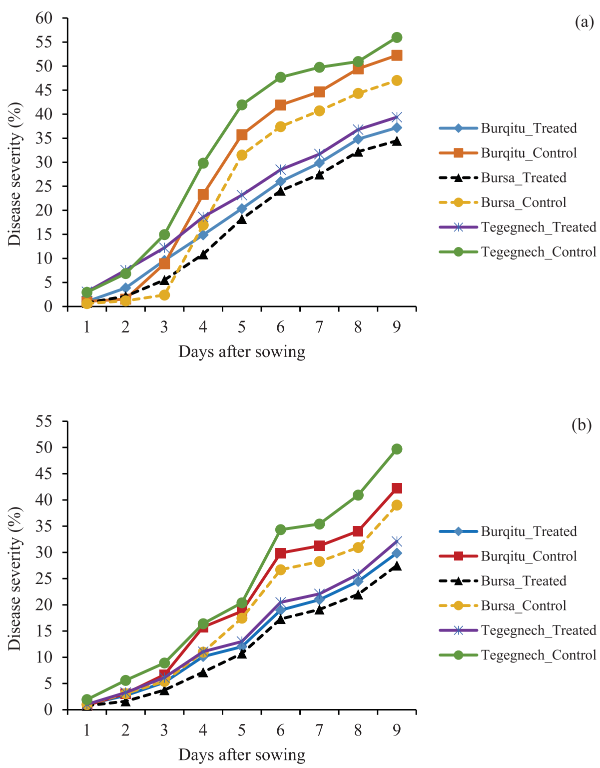

Figure 1. Progress of ascochyta blight of field pea as influenced by combined use of varieties and fungicides at Bonke (a) and Chencha (b), Southern Ethiopia, during the 2020 and 2021 main cropping seasons (Note: 1 = 40 and 37, 2 = 48 and 45, 3 = 56 and 53, 4 = 64 and 61, 5 = 72 and 69, 6 = 80 and 77, 7 = 88 and 85, 8 = 96 and 93, and 9 = 104 and 101 DAS during 2020 and 2021 at Bonke; and 1 = 38 and 41, 2 = 46 and 49, 3 = 54 and 57, 4 = 62 and 65, 5 = 70 and 73, 6 = 78 and 81, 7 = 86 and 89, 8 = 94 and 97, and 9 = 102 and 105 DAS during 2020 and 2021 at Chencha, respectively).

Agronomic characters

Growth parameters

Highly significant ($P < 0.001$) variations were observed in NPP, NSPP, PH, and SC among fungicides, field pea varieties, and their interactions both at Bonke and Chencha areas (Table 4). Consistently, the highest and the lowest growth parameters were measured from Othello-Top treated and untreated plots of each respective field pea variety, respectively. For instance, the highest mean NPP (10.3), NSPP (23.2), PH (161 cm) and SC (444) of Bursa were recorded from Othello-Top treated plots, while the lowest mean NPP of 7.78, NSPP of 14.8, PH of 138 cm and SC of 247 were recorded from control plots of Bursa at Bonke. Similar observations were recorded for other varieties as well. Moreover,

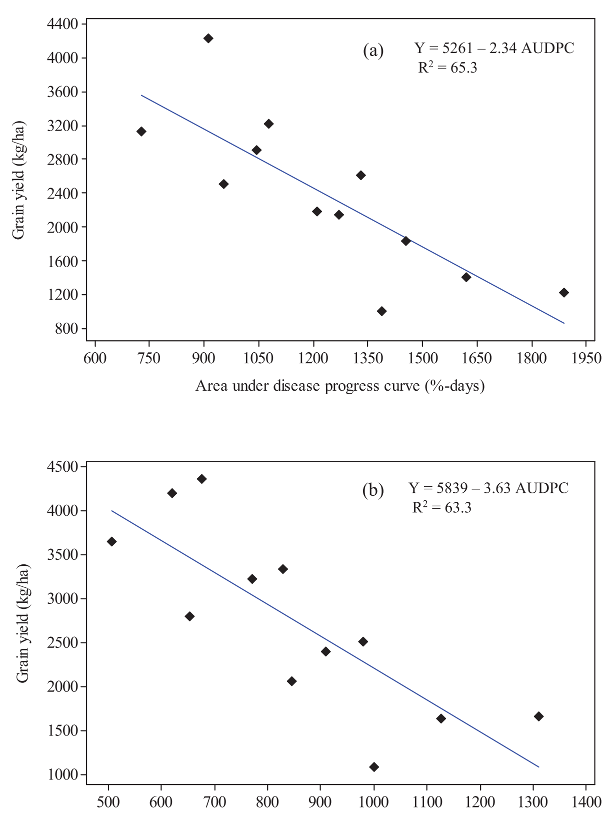

Figure 2. Estimation of relationships between losses in grain yield and area under disease progress curve (AUDPC) of ascochyta blight at Bonke (a) and Chencha (b), Southern Ethiopia, during the 2020 and 2021 main cropping seasons.

significantly better growth parameters were also noticed from Matico and Carbonchlor covered plots of each variety compared with control treatments.

At Chencha areas, control plots of Bursa, Burqitu and Tegegnech recorded the lowest mean plant height (137, 159 and 147 cm), stand count (177, 232 and 213), NPP (6.75, 8.17 and 7.04) and NSPP (17.8, 19.5 and 19.2) in that order of presentation in both cropping seasons. On the contrary, fungicide treated plots registered more improved growth parameters in the range of 140–158 cm of PH, 229–336 of SC, 7.46–9.26 of NPP and 19.7–22.1 of NSPP of variety Bursa over that of control plots. Closely similar scenarios were noted for growth parameters of Matico, Carbonchlor and Othello-Top treated plots of Burqitu and Tegegnech in both years. Comparatively, field pea varieties performed better with Othello-Top application, followed by Matico spraying at both locations in the cropping seasons.

Hundred seed weight and grain yield

Field pea varieties sprayed with fungicides showed very highly significant ($P < 0.0001$) variations in mean HSW and grain yield at both sites in the cropping years (Table 4). Accordingly, fungicide treated plots of Burqitu (29.4–31.3 g), Bursa (26.6–30.5 g) and Tegegnech (24.8–26.4 g) recorded the heaviest HSW as compared to their respective control plots at Bonke. Similarly, control plots of field pea varieties weighed the lowest (23.0–24.2 g) HSW at Chencha areas. Regarding grain yield, unsprayed plots gained low grain yield as compared to fungicide sprayed plots at both locations. For example, control plots of Burqitu (1.40×10^3 kg ha^{-1}), Bursa (1.01×10^3 kg ha^{-1}) and Tegegnech (1.22×10^3 kg ha^{-1}) obtained even lower grain yield than the overall means of each variety, which were 2.86×10^3, 2.21×10^3 and 2.03×10^3 kg ha^{-1} in that order at Bonke. Among fungicides, Othello-Top and Matico applications improved grain yield of Bursa, Burqitu and Tegegnech by 43.7 and 15.2%, 62.3 and 23.5%, and 58.9 and 16.8% as compared to Carbonchlor spraying at Bonke, respectively. The same trend was noticed for each variety at Chencha.

Moreover, fungicide spraying versus control treatment wise analysis showed that Othello-Top, Matico and Carbonchlor applications enhanced grain yield by 211, 150 and 117% (Bursa), 204, 130 and 86.5% (Burqitu) and 140, 76.2 and 50.8% (Tegegnech) as compared to control plots of each respective field pea varieties considered in the study in that order of appearance at Bonke. At Chencha areas, application of Othello-Top increased grain yield by 239% of Bursa, 158% of Burqitu and 165% of Tegegnech; and Matico spraying also improved grain yield of Bursa, Burqitu and Tegegnech by 160, 97.9 and 103% over the control plots, respectively. Furthermore, Carbonchlor based ascochyta blight management caused 47.2–91.0% grain yield gain compared with untreated plots of field pea varieties during the cropping years. Even though higher overall mean grain yield was harvested at Chencha (2.74×10^3 kg ha^{-1}) than Bonke areas (2.37×10^3 kg ha^{-1}), test varieties showed variable performances across locations (Table 4).

Relative yield loss of field pea due to ascochyta blight

The use of an integrated management scheme for ascochyta blight strongly influenced the relative yield advantages as well as losses of field peas as compared to unsprayed plots at both Bonke and Chencha. Thus, the mean relative grain yield losses computed for each treatment combination against the maximum protected (Othello-Top treated) plots across locations are presented in Table 5. Control plots of Bursa, Burqitu and Tegegnech recorded the highest grain yield loss of 67.89, 67.05 and 58.26% compared with Othello-Top treated plots of each variety, due to ascochyta blight in that order at Bonke. Among fungicides, Othello-Top application reduced yield loss by 30.4 and 19.9% (Bursa), 38.6 and 24.1% (Burqitu) and 37.1 and 26.5% (Tegegnech) when compared with fungicides Matico and Carbonchlor at Bonke, respectively. However, Matico and Carbonchlor applications increased grain yield gain of Bursa (70.8 and 55.2%), Burqitu (64.9 and 42.5%) and Tegegnech (54.6 and 36.4%) over unsprayed plots of each variety, respectively, at Bonke. At Chencha, application of Matico lowered grain yield loss by 46.5% (Bursa), 45.8% (Burqitu) and 44.8% (Tegegnech) compared with Carbonchlor covered plots. Comparatively, untreated plots of each variety recorded grain yield losses of 61.3–70.5% in the cropping years at Chencha (Table 5).

Association of ascochyta blight with grain yield of field pea

An integral regression model was used to predict yield loss due to ascochyta blight in the cropping seasons. In the model, AUDPC was considered as a predictor variable and grain yield was regarded as a response variable (Figure 2(a,b)). As demonstrated in the figure, when summative disease pressure increased, grain yield decreased and approached to the horizontal axis, implying a true inverse relationship between AUDPC and yield performance of field pea varieties studied at both experimental sites in the cropping years. In this regard, the regression model explained 65.3% (Bonke) and 63.3% (Chencha) of yield loss in field pea due to ascochyta

Table 4. Interaction effects of variety × fungicide application on agronomic performance of field pea at Bonke and Chencha, Southern Ethiopia, during the 2020 and 2021 main cropping seasons.

Treatment combination		Field pea agronomic parameters, Bonke [1]						Field pea agronomic parameters, Chencha [1]					
Variety	Fungicide	PH (cm)	SC	NPP	NSPP	HSW (g)	GY (kg ha^{-1})	PH (cm)	SC	NPP	NSPP	HSW (g)	GY (kg ha^{-1})
Burqitu	Carbonchlor	165^{cd}	385^{bc}	13.4^{bc}	25.9^{ab}	30.2^{ab}	$2.60 \times 10^{3b–d}$	163$^{b–d}$	327^{bc}	8.97^{bc}	18.6^{de}	25.2^{de}	2.40×10^{3de}
	Matico	185^{b}	431^{ab}	15.0^{b}	26.1^{ab}	29.4$^{a–c}$	3.22×10^{3b}	186^{ab}	326^{bc}	9.68^{b}	22.1$^{b–d}$	25.2^{de}	3.23×10^{3bc}
	Othello-Top	208^{a}	451^{a}	18.8^{a}	30.3^{a}	31.3^{a}	4.24×10^{3a}	194^{a}	391^{ab}	12.1^{a}	24.6^{ab}	26.2^{cd}	4.21×10^{3a}
	Unsprayed	148$^{c–g}$	308de	10.9^{cd}	17.9$^{d–f}$	26.1$^{b–d}$	1.40×10^{3fg}	159^{cd}	232de	8.17$^{b–d}$	19.5$^{c–e}$	23.2^{e}	1.63×10^{3f}
Bursa	Carbonchlor	147$^{d–g}$	354^{cd}	6.46^{e}	17.5$^{d–f}$	26.6^{bc}	2.18×10^{3de}	140^{d}	229^{e}	7.46^{cd}	19.7$^{c–e}$	28.7^{c}	2.05×10^{3f}
	Matico	167^{c}	409^{ab}	8.59^{de}	19.9^{cd}	27.5$^{a–c}$	2.51×10^{3cd}	158^{cd}	292^{cd}	9.26^{b}	20.1$^{c–e}$	31.7^{b}	2.79×10^{3cd}
	Othello-Top	161$^{c–e}$	444^{a}	10.3^{cd}	23.2^{bc}	30.5^{ab}	3.13×10^{3bc}	142^{d}	336^{bc}	8.99^{bc}	22.1$^{b–d}$	35.8^{a}	3.64×10^{3b}
	Unsprayed	138$^{f–h}$	265^{e}	7.78^{de}	14.8^{ef}	24.8^{cd}	1.01×10^{3g}	137^{d}	176^{e}	6.75^{d}	17.8^{e}	24.2^{de}	1.07×10^{3g}
Tegegnech	Carbonchlor	134^{gh}	297^{e}	7.89^{de}	16.9$^{d–f}$	25.0^{cd}	1.83×10^{3ef}	160^{cd}	294^{cd}	9.11^{bc}	22.4$^{a–c}$	24.8^{de}	2.51×10^{3de}
	Matico	144$^{e–g}$	388^{bc}	8.52^{de}	19.3$^{c–e}$	26.4^{bc}	2.14×10^{3e}	164^{bcd}	350^{bc}	9.74^{b}	23.9^{ab}	27.1^{cd}	3.34×10^{3b}
	Othello-Top	156$^{c–f}$	410^{ab}	10.3^{cd}	21.4^{dc}	24.8^{cd}	2.91×10^{3bc}	179$^{a–c}$	414^{a}	12.6^{a}	25.6^{a}	26.6^{cd}	4.36×10^{3a}
	Unsprayed	122^{h}	205^{f}	6.58^{e}	13.5^{f}	21.7^{d}	1.22×10^{3fg}	147^{d}	213^{e}	7.04^{d}	19.2$^{c–e}$	23.0^{e}	1.65×10^{3f}
Mean		156	362	10.4	20.6	27.0	2.37×10^{3}	161	298	9.16	21.3	26.8	2.74×10^{3}
CV (%)		9.83	11.6	24.6	17.7	12.8	22.41	12.7	17.1	14.4	12.6	8.35	14.27
P value		<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

[1]PH: Plant height; SC: Stand count; NPP: Number of pods per plant; NSPP: Number of seeds per pod; HSW: Hundred seed weight; and GY: Grain yield. CV: Coefficient of variation. Mean values in the same column with different letters represent significant variation at 5% probability level.

blight. For example, the regression trend line showed that for every one unit increase in AUDPC value, there was 2.34 unit grain yield loss at Bonke and 3.63 unit grain yield loss at Chencha. Moreover, the estimated values indicated that an increase in mean values of AUDPC caused a noticeable reduction in grain yield of the tested field pea varieties, irrespective of the fungicides applied and their combinations. Hence, the linear regression demonstrated that for each unit increase in AUDPC, there was 2.34 kg ha^{-1} and 3.63 kg ha^{-1} grain yield loss in the tested field pea varieties at Bonke and Chencha, respectively.

Economic feasibility analysis

Significant variations in the net benefit and benefit–cost ratio were observed among the treatments (Table 6). At both locations, the pooled results of the two cropping seasons revealed that combination of the variety Burqitu and Othello-Top showed the highest net benefit (\$$2.35 \times 10^3$ and 2.27×10^3 ha^{-1}), followed by Matico (\$$1.86 \times 10^3$ and 1.78×10^3 ha^{-1}) integrated with the same variety at Bonke and Chencha, respectively. Whereas, the lowest net benefits of \$$0.42 \times 10^3$ ha^{-1} at Bonke and 0.34×10^3 ha^{-1} at Chencha were recorded from control plots of Bursa. Similarly, the integration of Burqitu and Othello-Top, which exhibited the highest net benefit, also showed the highest benefit–cost ratio of 4.77 (Bonke) and 3.76 (Chencha). Of course, the lowest (1.10 and 0.69) benefit–cost ratio was recorded from the unsprayed plot of variety Bursa at Bonke and Chencha areas in that order, though variety Bursa demonstrated resistance to ascochyta blight at both locations during the epidemic periods of the two years (Table 3). Overall, the use of variety Burqitu in combination with Othello-Top, followed by Matico, was the most profitable management option over the other treatments and their combinations.

Discussion

Ascochyta blight complex remains an economically important challenge of field pea production, and the disease is very commonly occurring in field pea growing areas of the world (Gorfu 2004; Bretag et al. 2006; Gan et al. 2006; Davidson and Kimber 2007; Gossen et al. 2011; Davidson 2012; Khan et al. 2013; Česnulevičienė et al. 2014; Liu et al. 2016; Tegegn and Teshome 2017; Tran 2017; GRDC 2018; Walela et al. 2018). In the present study, high disease pressure had been observed across the study areas, irrespective of treatments (Tables 2 and 3), which could be associated with year-round cultivation of field pea and weather

Table 5. Effects of variety × fungicide interactions on relative yield loss of field pea due to ascochyta blight at Bonke and Chencha, Southern Ethiopia, during the 2020 and 2021 main cropping seasons.

Treatment combination		Relative yield loss, Bonke[a]				Relative yield loss, Chencha[a]			
Variety	Fungicide	Yield (kg ha^{-1})	Relative yield (%)	Yield loss (%)	Yield increase (%)	Yield (kg ha^{-1})	Relative yield (%)	Yield loss (%)	Yield increase (%)
Burqitu	Carbonchlor	2.60×10^3	61.44	−38.56	86.48	2.40×10^3	57.05	−42.95	47.23
	Matico	3.22×10^3	75.86	−24.14	130.22	3.23×10^3	76.72	−23.28	97.98
	Othello-Top	4.24×10^3	100	0.00	203.52	4.21×10^3	100	0.00	158.06
	Unsprayed	1.40×10^3	32.95	−67.05	0.0	1.63×10^3	38.75	−61.25	0.0
Bursa	Carbonchlor	2.18×10^3	69.59	−30.41	116.72	2.05×10^3	56.32	−43.68	90.99
	Matico	2.51×10^3	80.14	−19.86	149.56	2.79×10^3	76.65	−23.35	159.97
	Othello-Top	3.13×10^3	100	0.00	211.40	3.64×10^3	100	0.00	239.15
	Unsprayed	1.01×10^3	32.11	−67.89	0.0	1.07×10^3	29.49	−70.51	0.0
Tegegnech	Carbonchlor	1.83×10^3	62.94	−37.06	50.78	2.51×10^3	57.39	−42.61	52.14
	Matico	2.14×10^3	73.54	−26.46	76.18	3.34×10^3	76.46	−23.54	102.71
	Othello-Top	2.91×10^3	100	0.00	139.57	4.36×10^3	100	0.00	165.12
	Unsprayed	1.22×10^3	41.74	−58.26	0.0	1.65×10^3	37.72	−62.28	0.0

[a]Yield increase for each variety over the control was determined as proportion of the difference between sprayed and unsprayed plots at each location in the cropping years.

conditions that would be responsible for the production and spread of inocula sources for each cropping season. That is, the seed-to-seedling transmission of the pathogen could be considered as the major source of primary inoculum in the new field pea growing areas (Xue et al. 1996a; Xue et al. 2003; Gorfu 2004; Gan et al. 2006; Davidson and Kimber 2007; Walela et al. 2018). Of course, the demand for quality seeds used to rise in Ethiopia as farmers started realising the benefits of quality seeds (Keneni et al. 2001), though almost all farmers use their own seed stock for planting their fields every year, presumably aggravating the disease (Gemeda et al. 2001).

On the other hand, poor residue management practices might also enhance the accumulation of inoculum of the pathogen to initial infection and secondary dispersal and disease gradients in the study areas. In this regard, Bretag et al. (2006) pointed out that when peas are grown in fields previously cropped to peas, ascochyta causing pathogens can survive as mycelium on infected pea trash, or in the soil as sclerotia and chlamydospores and many plants are likely to be infected and develop severe root rot. In addition, Warkentin et al. (1996) found out pycnidiospores are produced on infected plant residue during moist weather and can be carried by rain splash to healthy plants and favoured secondary spread under moist conditions. Thus, deep-burying or burning of chickpea (Gossen 2001; Gan et al. 2006) and field pea (Zhang et al. 2005; Davidson and Kimber 2007; Walela et al. 2018) stubble could minimise stubble-borne inoculum for the following cropping years.

Even though variety × fungicide applications resulted in inconsistent responses in field pea varieties across the study locations, slight variations were noticed between experimental areas for disease and yield components. Bonke areas recorded relatively higher ascochyta blight progression and severity than Chencha site (Tables 2 and 3), which could be partly explained by the weather conditions of the two study sites. In the former location, there were comparably warm temperature, high rainfall with many rainy days and high relative humidity (≥70%) during the main epidemic periods which purported to favour the development and progression of ascochyta blight in the growing seasons (Table 1). Ascochyta blight severity and pycnidia are reported to increase with temperature from 15°C to 20°C and decrease from 20°C to 30°C (Roger et al. 1999a, 1999b); and the disease can develop rapidly during wet periods and moderate temperatures where small flecks and spots quickly enlarge, coalesce and form necrotic lesions and cause general blighting (Roger et al. 1999b; Bretag et al. 2006). Also, a temperature of below 15°C and a humidity of more than 70% are optimum for conidial and/or ascospores germination and initiation of infections (Davidson 2012; Tran 2017). Moreover, Xue et al. (2003) reported that low ascochyta blight severity could likely be related to less frequent rains and lower precipitation that would create dry conditions and disfavour disease development during the study years.

Combined use of field pea varieties and fungicide applications significantly reduced ascochyta blight components and progression at both experimental areas over years. Fungicide applications reduced the last-three terminal mean severities by 15.9–44.3 (Bursa), 19.5–41.2% (Burqitu) and 25.0–45.6 (Tegegnech) compared with unsprayed plots at Bonke (Table 2). Similarly, higher (0.45–0.67 units day^{-1}) progression rates were obtained from control plots than that of treated plots of each variety at Bonke. Related trends were recorded at Chencha areas (Table 3). Moreover, variable levels of progression, severity, and apparent infection rates were also noticed among field pea varieties and

Table 6. Economic feasibility analysis of management of field pea ascochyta blight through varieties and fungicides at Bonke and Chencha, Southern Ethiopia, during the 2020 and 2021 main cropping seasons.

Treatment combination		Bonke experimental areas[a]						Chencha experimental areas[a]					
		Grain yield (kg ha^{-1})			AGY	NB		Grain yield (kg ha^{-1})			AGY	NB	
Variety	Fungicide	2020	2021	Pooled	(kg ha^{-1})	($ ha^{-1})	BCR	2020	2021	Pooled	(kg ha^{-1})	($ ha^{-1})	BCR
Burqitu	Carbonchlor	3.23×10^3	1.92×10^3	2.60×10^3	2.34×10^3	1441.55	2.96	1.92×10^3	2.88×10^3	2.40×10^3	2.16×10^3	1.36×10^3	2.28
	Matico	3.89×10^3	2.54×10^3	3.22×10^3	2.89×10^3	1860.09	3.82	2.54×10^3	3.92×10^3	3.23×10^3	2.91×10^3	1.78×10^3	2.98
	Othello-Top	4.36×10^3	3.52×10^3	3.94×10^3	3.55×10^3	2351.20	4.77	3.38×10^3	5.05×10^3	4.22×10^3	3.80×10^3	2.27×10^3	3.76
	Unsprayed	1.43×10^3	1.36×10^3	1.39×10^3	1.26×10^3	688.10	1.80	1.36×10^3	1.90×10^3	1.63×10^3	1.47×10^3	0.61×10^3	1.24
Bursa	Carbonchlor	2.98×10^3	1.39×10^3	2.18×10^3	1.96×10^3	1150.96	2.37	1.39×10^3	2.72×10^3	2.05×10^3	1.85×10^3	1.07×10^3	1.79
	Matico	2.95×10^3	2.07×10^3	2.51×10^3	2.26×10^3	1377.35	2.83	2.07×10^3	3.52×10^3	2.79×10^3	2.51×10^3	1.29×10^3	2.17
	Othello-Top	3.61×10^3	2.65×10^3	3.13×10^3	2.82×10^3	1799.02	3.65	2.65×10^3	4.62×10^3	3.63×10^3	3.27×10^3	1.72×10^3	2.85
	Unsprayed	1.27×10^3	0.74×10^3	1.01×10^3	0.91×10^3	420.58	1.10	0.71×10^3	1.44×10^3	1.07×10^3	0.97×10^3	0.34×10^3	0.69
Tegegnech	Carbonchlor	2.09×10^3	1.58×10^3	1.83×10^3	1.65×10^3	913.26	1.88	1.58×10^3	3.44×10^3	2.51×10^3	2.26×10^3	0.83×10^3	1.40
	Matico	1.99×10^3	2.28×10^3	2.14×10^3	1.93×10^3	1124.74	2.31	2.28×10^3	4.40×10^3	3.34×10^3	3.01×10^3	1.05×10^3	1.75
	Othello-Top	2.93×10^3	2.89×10^3	2.91×10^3	2.62×10^3	1648.25	3.34	2.90×10^3	5.83×10^3	4.36×10^3	3.93×10^3	1.57×10^3	2.60
	Unsprayed	1.40×10^3	1.03×10^3	1.22×10^3	1.09×10^3	564.21	1.48	1.03×10^3	2.32×10^3	1.67×10^3	1.51×10^3	0.48×10^3	0.99

[a]AGY: Adjusted grain yield (at 10% down); NB: Net benefit; and BCR: Benefit-cost ratio. Mean unit price of grain yield per kg during the 2020 (0.81 and 0.91 $) and 2021 (0.72 and 0.80 $) cropping years were 0.76 and 0.85 $ [at the exchange rate of 1$ = ETB 39.37 (2020) and 49.9 (2021)] at the time of marketing at Bonke and Chencha, respectively.

fungicides. Several other studies also documented different results regarding the synergetic effects of host resistance and fungicide spraying to control ascochyta blight complex (Dereje and Sangchote 2003; Xue et al. 2003; Bretag et al. 2006; Gan et al. 2006; Česnulevičienė et al. 2014; Liu et al. 2016).

Despite the fact that controlling efficacy of foliar fungicides largely depends on (1) the level of host resistance, (2) the efficacy of the fungicide, (3) foliar coverage achieved, (4) disease pressure, and (5) weather conditions (Gan et al. 2006), a significant reduction in apparent infection rate, progression pattern, severity and AUDPC in the present study could be due to the suppressive roles of the fungicides along with the genetic background of the pea varieties to subdue infectivity of the pathogens, lesion development, infective inoculum production and spread, and establishment of secondary infection in the field. Integration of fungicide and host resistance could also decrease germination and growth of the pathogens. Similarly, findings of an evaluation study conducted in Sinana for two cropping years showed that foliar application of benomyl at a rate of 2.5 ka ha^{-1} at 7 days interval reduced disease parameters, while the control plots recorded the highest disease (Tegegn and Teshome 2017). On the other hand, Gan et al. (2006) pointed out that post-infection application is only effective if the fungicides are capable of eliminating established infections and are active in plants for a certain period of time. Accordingly, systemic fungicides, which were also used in this study, are the logical choice for post-infection sprays because these fungicides can be translocated within the plants in sufficient quantity to protect foliage from infection (Shtienberg et al. 2000).

Moreover, field pea crops are the most sensitive to fungicides (Gossen et al. 2011), and ascochyta blight severity can be reduced with one or two applications of fungicides per season (Gossen et al. 2001; Gossen et al. 2008), if applied at appropriate growth stages of the crop. Previous studies demonstrated that foliar application of fungicides did not consistently increase seed yield despite the reduction in disease and associated yield increases (Warkentin et al. 2000). But it is highly likely that previously ineffective cultural management and fungicidal control measures may re-emerge as effective and profitable practice when used in conjunction with partially-resistant germplasm (Khan et al. 2013). In an experiment to evaluate the effects of chlorothalonil in controlling mycospherella blight in field pea from 1999 to 2000 also concluded that fungicide application enhanced yield components and reduced disease severity in cultivars though cultivar × fungicide interactions were not significant in three years due to the prevailing weather conditions (Xue et al. 2003). Furthermore, Warkentin et al. (1996) indicated that fungicide treatments (chlorothalonil and benomyl) significantly reduced the final ascochyta blight rating at variable applications in AC Tamor and Radley field pea cultivars at two locations in Manitoba in 1993 and 1994.

Although several field pea varieties have been developed and released to different agro-ecologies in Ethiopia, none of them offer a higher degree of genetic resistance to ascochyta blight and/or all fungi species of ascochyta complex, which is due to the presence of three or more pathogens and physiological specialisation within the pathogen species (Zhang et al. 2003; Pande et al. 2005; Bretag et al. 2006; Zhang et al. 2007; McMurray et al. 2011; Khan et al. 2013; Liu et al. 2016). Therefore, continuous screening of field pea collections should be made to find source of resistance to the target disease. In this study, the test field pea varieties exhibited marked differences for ascochyta complex disease components at Bonke and Chencha areas (Tables 2 and 3, Figure 1). Previous studies also reported that pea genotypes showed some levels of variations for the disease under various conditions across pea growing areas in the world (Warkentin et al. 1996; Xue et al. 2003; Chongo et al. 2004; Gorfu 2004; Pande et al. 2005; Bretag et al. 2006; Gan et al. 2006; McMurray et al. 2011; Khan et al. 2013; GRDC 2018).

Variety Bursa and Burqitu performed better than Tegegnech to slow down blight progress rate under both fungicide applications and control conditions across locations in the cropping seasons. Such noticeable variations observed among pea varieties could be attributed to the genetic background and resistance level of the varieties to delay disease progression and development; and variable response of pea varieties to fungicides used in terms of reducing disease components and enhancing seed yield and related parameters. Similarly, a fungicide efficacy study involving ten pea cultivars with different leaf types, market classes, seed sizes, plant heights, and maturities noted that cultivars were significantly different for disease severity, yield, thousand seed weight (TSW), and seed infection each year (Xue et al. 2003). Of the ten cultivars studied, Radley was the most resistant with or without chlorothalonil treatment, while Carrera and Keoma were equally the most susceptible cultivars (Xue et al. 2003). Khan et al. (2013) also outlined that though no completely effective source of resistance has been found, some lines from Europe, North America and Asia showed moderate resistance and even several varieties adapted to various parts of the world have a useful degree of resistance.

Comparatively, Tegegnech (susceptible) was more responsive to fungicide application in lowering of blight establishment at both locations, followed by Burqitu, which is reported to be moderately resistant in the study areas (Tables 2 and 3, Figure 1). The findings were found to be similar to those described by Warkentin et al. (2000) who demonstrated that the beneficial effects of fungicides can be greater for susceptible cultivars than for the moderately resistant cultivars in the control of mycosphaerella blight. Related to the current findings, Mengesha et al. (2021) reported that foliar application of fungicides with faba bean cultivars reduced chocolate spot components as susceptible cultivars usually respond more to fungicide sprays than relatively tolerant cultivars. Anyway, Davidson and Kimber (2007) suggested integrated disease management involves a combination of cultivar resistance, seed and crop hygiene, seed and foliar fungicides and appropriate sowing dates though the complexity of the pathogen and inter-relationship with resistance and environment might compromise the effectiveness of the option.

Field pea varieties sprayed with fungicides showed very highly significant ($P < 0.0001$) variations in grain yield and yield components, with some exceptions, at both locations (Table 4). Integration of host resistance and fungicide applications enhanced yield through decreasing disease parameters. In this regard, fungicide treated plots of Bursa (26.6–30.5 g), Burqitu (29.4–31.3 g) and Tegegnech (24.8–26.4 g) recorded the heaviest hundred seed weight; and fungicide applications enhanced grain yield by 211, 150 and 117% (Bursa), 204, 130 and 86.5% (Burqitu) and 140, 76.2 and 50.8% (Tegegnech) as compared to control plots at Bonke. Among the fungicides, Othello-Top and Matico sprayings improved grain yield of Bursa, Burqitu and Tegegnech by 43.7 and 15.2%, 62.3 and 23.5%, and 58.9 and 16.8% when compared with Carbonchlor spraying at Bonke, respectively. Closely similar trends were noted for each variety at Chencha, except for some inconsistencies among the varieties in the cropping years.

The findings contended that using moderately resistant pea varieties with the right combination of fungicides could reduce ascochyta blight damages and yield losses, and increase yield gains in high disease pressure areas. Similarly, the overall observations of Xue et al. (2003) figured out that under the conditions of high disease pressure and high yield potential, fungicide applications were effective in reducing both disease severity and seed infection, and increasing yield and TSW. The same author reported that chlorothalonil reduced seed infection by 19.2% and increased yield by 6.4%, and TSW by 0.9–5.1% among cultivars. Also, in a fungicidal trial study, Warkentin et al. (1996) reported that double and triple applications of chlorothalonil and triple applications of benomyl significantly reduced final ascochyta blight, and increased seed weight and yield over other fungicides compared. Moreover, the present study revealed that yield components of field pea varieties were more or less improved due to the integration of host resistance and triple applications of fungicides. Related to it, Tivoli et al. (1996) indicated that severe ascochyta blight infections can reduce number of seeds per plant when compared with healthy plants. On the other hand, the maximum NPPP, NSPP and HSW were recorded from plots sprayed with benomyl at 7 days interval, while the lowest values of each component were obtained from control plots in both years at Sinana, Ethiopia (Tegegn and Teshome 2017).

In this study, variety × fungicide application strongly reduced relative yield loss (Table 5). For instance, control plots of Bursa (67.9%), Burqitu (67.1%) and Tegegnech (58.3%) recorded the highest grain yield loss compared with Othello-Top treated plots at Bonke. Applications of Matico and Carbonchlor also increased grain yield gain of Bursa (70.8 and 55.2%), Burqitu (63.9 and 42.5%) and Tegegnech (54.6 and 36.4%) over unsprayed plots, respectively, at Bonke in the cropping seasons. Similar observations were registered at Chencha areas. Yield loss in field pea is associated with severe ascochyta blight pressure likely due to conducive weather conditions, which could cause significant reduction in the photosynthesizing leaf area and a decrease in the photosynthetic efficiency of the leaf. Low net photosynthetic rate of diseased plants attained a positive correlation with an increase in disease scores (Garry et al. 1998). On the other hand, ascochyta blight can infect all above-ground parts of the crop and is characterised by necrotic lesions leading to breakage of stem and defoliation of leaves that result in severe yield reductions (Davidson and Kimber 2007; Panicker and Ramraj 2010). Thus, substantial yield losses in pea varieties due to ascochyta in the study areas would also be well justified as it used to affect yield components, and a yield loss of 25–50% had been reported due to a reduction in yield related components of the crop (Warkentin et al. 1996).

An integral regression model that related AUDPC and grain yield demonstrated that 65.3% (Bonke) and 63.3% (Chencha) of yield losses in field pea were due to ascochyta blight in both years (Figure 2). Earlier studies also documented similar relationships among disease and yield parameters in field pea (Tivoli et al. 1996; Davidson 2012; Česnulevičienė et al. 2014; Tegegn and Teshome 2017; Teferi et al. 2018; Bitew et al. 2022; Yitayih et al. 2022). The negative association between AUDPC and yield could indicate that such disease parameter is an important element to estimate losses in grain yield of field pea. That is, the disease usually accelerates seed desiccation, reduces seed weight, disturbs nutrient metabolism and reduces the photosynthetic potential of plants, and thus yield accumulation (Garry et al. 1998).

Economic feasibility analysis exhibited that integration of variety Burqitu with Othello-Top and Matico fungicides provided the highest net benefit ($\$2.35 \times 10^3$ and 2.27×10^3 ha^{-1}, and $\$1.86 \times 10^3$ and 1.78×10^3 ha^{-1}) at Bonke and Chencha in that order in the two years. Likewise, the same treatment combination obtained the highest mean benefit–cost ratios of 4.77 and 3.76 as compared to other treatments at Bonke and Chencha, respectively (Table 6). Disparities in the net benefit and benefit–cost ratio in this study could be due to treatment performance, disease pressure, weather conditions, and overall costs of production and marketing of grain yields at harvest. Note that the choice of commodity that the market needs, time of crop production, total input cost of production, quality and quantity of goods, and the market price of the goods at the time of commercialising significantly affect economic benefits from agricultural business (CIMMYT 1988). To this effect, the combined use of variety Burqitu with Othello-Top, followed by Matico, was found to be the most profitable management option as indicated by the highest monetary advantage. Other related research results by Bretag et al. (2003) and Davidson and Kimber (2007) also showed the profitability of integrated management package against ascochyta blight in other areas.

It can be concluded that combined use of host resistance and fungicide applications slowed down disease progression and pressure, minimised relative yield loss and enhanced agronomic performances of field pea varieties across locations in the cropping years. Application of Matico and Othello-Top fungicides significantly reduced ascochyta blight severity, rate of development, and comparably minimised yield loss, irrespective of the field pea varieties. Among the fungicides considered, triple applications of Othello-Top, followed by Matico, significantly lowered disease components and yield loss and increased yield, hundred seed weight and other productivity indicators. Moreover, a varietal difference in susceptibility to ascochyta blight implied that variety Tegegnech was more susceptible than variety Bursa and Burqitu at both locations in the cropping seasons. However, yield response was not consistent across locations. From an economics perspective, combination of the variety Burqitu and Othello-Top showed the highest net benefit (\$$2.35 \times 10^3$ and 2.27×10^3 ha^{-1}), followed by Matico (\$$1.86 \times 10^3$ and 1.78×10^3 ha^{-1}) integrated with the same variety at Bonke and Chencha, respectively. Integration of Burqitu and Othello-Top also obtained the highest benefit–cost ratio of 4.77 (Bonke) and 3.76 (Chencha) in the cropping years. Thus, the combined use of field pea variety Burqitu with triple application of Othello-Top, followed by Matico, found to be the most profitable management option and it could be suggested for field pea growers in the study areas. Future research should focus on the integration of agronomic (such as sowing date, field hygiene, clean seed, and crop rotation) practices, host resistance, seed treatment and alternate application of fungicides to ensure field pea production; and pathogen population study and screening of available field pea genotypes should also be considered.

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