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Trade-Offs in Field Pea (*Pisum sativum* L.) Health: Staking, Variety, and Fungicide Integration Curb Powdery Mildew Epidemics and Enhance Agronomic Performance but Suppress Symbiotic Nodulation

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ABSTRACT

Field pea, a versatile cool-season crop that is largely produced for grain and green pods, has trouble being productive worldwide, including in Ethiopia, where it is mainly affected by powdery mildew (PM, *Erysiphe pisi*). This study evaluated the effectiveness of staking, variety, and fungicide combinations on PM development, agronomic traits, nodulation, and yield reduction. Field studies were conducted in Bonke and Chencha, southern Ethiopia, in 2020 and 2021. The experiment was set up with a split-split-plot design with three replicates, where staking, varieties, and fungicides were assigned to main plots, subplots, and sub-subplots, respectively. Results showed that severity levels recorded in plots with Bursa variety, staking, and azostrobin + difenoconazole (Othello) fungicide spray were as low as 5.50%, 8.69%, and 10.01% at Bonke and 7.59%, 8.85%, and 11.74% at Chencha in the last three assessments. Sowing Bursa, Burqitu, and Tegegnech, along with staking and Othello fungicide spray, reduced the area under disease progress curve by 73.61%, 72.76%, and 69.37% at Bonke and 61.93%, 66.06%, and 64.00% at Chencha over respective control plots, respectively. Planting the Burqitu variety, combined with staking and Othello fungicide, resulted in the highest records for plant height (PH, 207.50 cm), number of productive pods per plant (NPP, 18.80), number of seeds per pod (NSP, 30.30), and hundred seed weight (HSW, 31.30 g) at Bonke. Highest PH (194.48 cm, Burqitu), NPP (12.57, Tegegnech), NSP (25.60, Tegegnech), and HSW (35.78 g, Bursa) were recorded from pea varieties treated with combined operations of staking and Othello fungicide at Chencha. Of treatments, Burqitu variety with staking and Othello fungicide yielded 4.24 and 4.21 t ha^{-1} at Bonke and Chencha, respectively. Staking and Othello combinations reduced yield loss by 79.54%, 77.63%, and 83.46% and improved yield by 431.67%, 345.28%, and 540.18% for Tegegnech, Burqitu, and Bursa varieties over unmanaged plots, respectively. However, fungicide spray considerably decreased nodulation, with Othello reducing effective nodules by 70.15% (Burqitu), 68.86% (Tegegnech), and 57.0% (Bursa). Staking with Burqitu and Othello achieved the highest net returns ($2538.14 and $2433.83 ha^{-1}) and benefit–cost ratios (6.95 and 5.54) in Bonke and Chencha, respectively. Thus, Burqitu variety, combined with staking and Othello fungicide, effectively reduces PM pressure, enhances yield, minimizes losses, and maximizes economic returns, making it a viable option for growers managing pea productivity. However, special attention is required regarding the benefits of nodules.

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1 | Introduction

Field pea (*Pisum sativum* L.) is a self-pollinating legume primarily cultivated for grain and pods, covering 7.41 million hectares globally in 2023, yielding 26.61 million metric tons (FAO 2023). China, India, and Pakistan are the largest producers (FAO 2023), while Ethiopia is the largest producer in Africa, with over 380,336 t from 220,195 ha in 2022 (FAO 2022). The crop is a source of income for producers (USDA 2022), rich in essential nutrients, and a major contributor to human diets and farmer income (Kumari and Deka 2021). By promoting nitrogen fixation and enhancing crop rotations and intercropping systems, the crop advances sustainable agriculture (Jensen et al. 2012). Moreover, it effectively interferes with some pathogens' life cycles during intercropping (Davidson and Kimber 2007).

Despite the significance of field peas, field pea productivity is adversely affected by various biotic and abiotic stresses, inadequate agricultural technologies, climate change, and ineffective pest management strategies worldwide (MoANR and EATA 2018; Takusewanya et al. 2018; Singh et al. 2024). In Ethiopia, the national average productivity stands at 1.61 t ha^{-1}, while southern Ethiopia averages 1.73 t ha^{-1} (CSA 2022), significantly lower than the global average of 4.14 t ha^{-1} (FAO 2022), which is approximately 2.48 times higher than Ethiopian productivity. Powdery mildew (PM), caused by *Erysiphe pisi* Sydow, is a major biotic factor limiting yield and has been reported in most pea-growing regions globally (Jarvis et al. 2002; Barilli et al. 2019). In Ethiopia, it significantly hampers productivity along with environmental factors, marking it as a critical challenge in pea cultivation (MoANR and EATA 2018; Ertiro and Haile 2022; Hordofa and Tamiru 2023).

E. pisi is an obligate airborne parasite that causes PM, a polycyclic pathogen capable of generating multiple generations in a single season. It survives the winter in crop debris, producing wind and rain-dispersed spores that infect new crops (Tiwari et al. 1999; Shafique et al. 2014). The pathogen thrives at higher elevations and is favored by warm temperatures (15°C–25°C) and high humidity during late growing seasons (Jarvis et al. 2002; Wspanialy and Moussa 2016). Factors such as inoculum density, strain pathogenicity, weather, host genetics, and agricultural practices impact its spread. Continuous cultivation of host crops, nearby alternate hosts, and infected debris contribute to the pathogen's persistence, potentially leading to epidemics (Falloon and Viljanen-Rollinson 2001; Jarvis et al. 2002). *E. pisi* can cause infections on all the aboveground parts of the plants; white, powdery, and grayish fungus patches appear on the upper surfaces of leaves, stems, and pods, resulting in a bluish-white coating that can be easily rubbed off, leading to reduced photosynthesis, premature drying, and shrunken seeds (Jarvis et al. 2002; Fondevilla and Rubiales 2012). Crop losses can reach 50%–100% (Suresh et al. 2025), with reported losses of 20%–30% under moderate conditions, peaking at 86% in severely affected varieties in Ethiopia (Yimam et al. 2020). These losses are attributed to reduced photosynthetic efficiency and altered water dynamics in infected plants (Ayres 1977; Jarvis et al. 2002). Hence, effective control measures targeting these conditions are essential to minimize yield losses in field peas. However, the appropriate strategies depend on variable agronomic practices and environmental factors, which remain uncertain in affected regions.

Management options such as early sowing, using early maturing varieties (Fondevilla and Rubiales 2012), frequent tillage, proper fertilization (Mieslerová et al. 2022), staking (Takusewanya et al. 2018; Hordofa and Tamiru 2023), varietal or crop diversification (Jensen et al. 2012; Villegas-Fernández et al. 2021), destroying residue, and crop rotation (Viljanen-Rollinson et al. 1998; Bailey et al. 2001), as well as using natural products, resistant varieties, biological agents, and fungicides (Fondevilla and Rubiales 2012), have been reported to manage PM globally. Under Ethiopian conditions, PM management heavily relies on planting resistant varieties (such as Burqitu, Adi, and Holeta, although their R-gene has succumbed), fungicide sprays, and cultural practices like early planting, staking, and crop rotation, largely employed by small-scale farmers. Occasionally, integrating approaches that combine cultural measures (such as adjusting planting times or staking) with resistant/tolerant varieties and resistant/tolerant varieties with fungicide applications, regardless of whether they are staked or not, is practiced by seed multiplier farmers, private investors, state farms, and research institutions for seed maintenance (MoANR and EATA 2018). Yet, the effects of plant diseases may not be sufficiently alleviated by the exclusive use of control measures. That is to say, sole use of cultural, host resistance, biological, and chemical tactics may have limitations in their success for disease reduction, mainly due to issues regarding alterations in agronomic practices, environmental changes, reductions in resistance gene durability, new strain development, and pesticide resistance (Agrios 2005). For instance, cultural measures only partly manage field pea PM by reducing inoculum levels in the field, the use of resistant varieties does not ensure consistency due to the limited durability of resistance genes and the variable biotypes in the *E. pisi* population (Tiwari et al. 1997), and repeated use of fungicides leads to resistance by the pathogen (Lucas et al. 2015).

Such phenomena encourage the operation of integrated management measures that combine various strategies, such as cultural practices, host resistance, and chemical methods. This approach represents the most effective method for managing plant diseases in many pathosystems (Campbell and Madden 1990; Madden et al. 2017). Previous reports suggested that the integration of varieties with either cultural practices, natural products, biological agents, fungicides, or combinations of more than two tactics had more promising options than independent operations in reducing PM pressure and boosting the agronomic performance of field peas (Fondevilla and Rubiales 2012; Hordofa and Tamiru 2023; Suresh et al. 2025). Specifically, Sansi (2013) and Jamal et al. (2025) found that a combination of varieties with fungicides, botanicals, or biological agents significantly lowered PM intensity and improved the agronomic traits of field peas in India. In this regard, Woldeyohannis et al. (2026) reported that a combination of varieties and fungicide applications exhibited a significant reduction in PM severity and enhanced field pea agronomic performance in Ethiopia. On the other hand, foliar spray does not affect the process of nodule formation in legumes (Cardillo et al. 2019), while fungicide applied as seed dressing has been shown to reduce nodulation (Santos et al. 2021). However, El-Kholy et al. (2021) contend that foliar spray increases nodulation compared with seed dressing. Other studies also indicated that integrating varieties with both cultural and

chemical tactics (Terefe et al. 2024), as well as with chemical tactics alone (Mengesha et al. 2025), improved agronomic traits and nodulation in common beans by reducing diseases that affect beans in Ethiopia.

However, there is a lack of empirical information about how combining staking, varieties, and fungicide spray can help with PM disease suppression and improve agronomic traits. It is also unclear if these approaches have a positive or negative impact on nodule development in field peas. Hence, combining pea varieties with varying degrees of resistance to PM with staking and fungicide foliar spray may be an alternative choice for PM management in Ethiopia. Additionally, integrative management measures that incorporate cultural practices and host resistance alongside fungicides are vital elements of sustainable agriculture; these methods are economically efficient and environmentally benign for managing plant diseases while minimizing risks to humans, animals, and nontarget organisms, as well as reducing fungicide residues, water body contamination, and the indiscriminate application of fungicides in Ethiopia. Thus, this investigation aimed to assess the effectiveness of integrated approaches, including staking, variety selection, and fungicide application, in reducing PM development, improving agronomic traits, reducing yield loss, and influencing nodule formation in field peas under field conditions.

2 | Materials and Methods

2.1 | Experimental Areas

Field experiments for the evaluation of combined application of cultural practices, pea varieties, and fungicides against PM development, agronomic performance, and nodulation were conducted at farmers' fields in Bonke and Chencha, southern Ethiopia, during the 2020 and 2021 main cropping seasons. Experimental sites were chosen based on their potential for field pea production and being hotspots for PM epidemics every year. The research site in Bonke is located at 06°04′53.47″ N, 037°18′33.69″ E, at an elevation of 2651 m a.s.l., while the site in Chencha is situated at 06°16′23.19″ N, 037°35′29.97″ E, at an elevation of 2668 m a.s.l. The study areas have a bimodal rainfall pattern, with the major rainy season lasting from July to November and the short rainy season occurring in March and June. The weather variables, which were obtained from the Ethiopian Meteorological Agency, Hawassa branch, for the study periods are displayed in Figure 1. Characteristic features of the soil at the study sites are acidic with low organic content (0.21%–1.13%) and a sandy-loam texture (MoANR and EATA 2016).

2.2 | Sources of Experimental Materials and Their Characteristics

Two cultural practices (with and without staking), three pea varieties (Burqitu, Bursa, and Tegegnech), and three fungicides (Carbonchlor, Othello-Top, and Matico) were utilized during the study. Bursa, Burqitu, and Tegegnech are classified as resistant, moderately resistant, and susceptible to PM, respectively. Seeds were obtained from Holeta Agricultural Research Centers, Ethiopia. The fungicides, Othello-Top 350

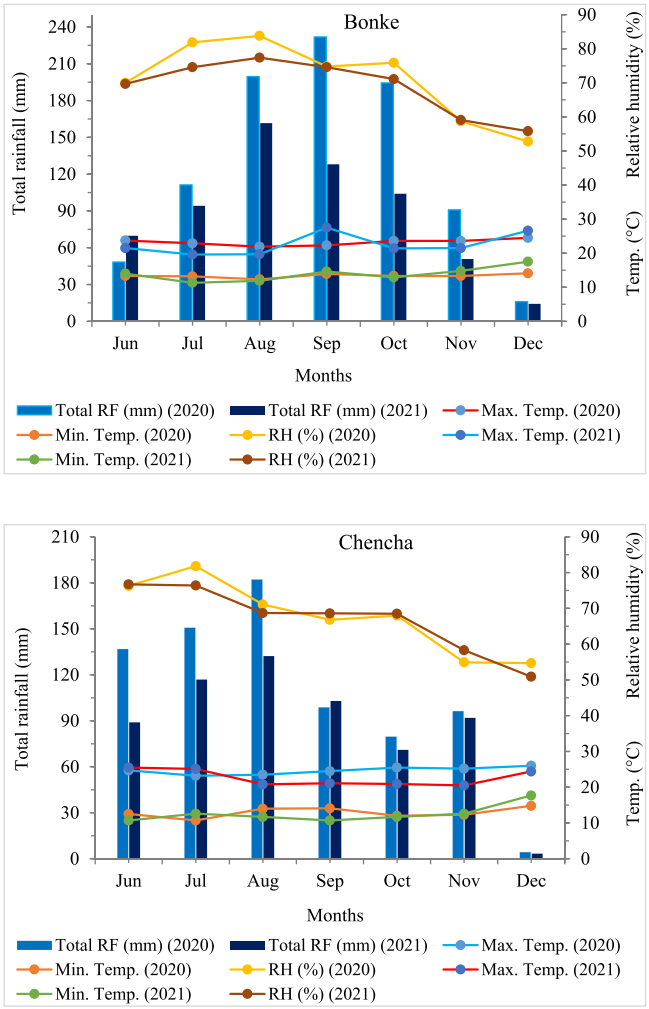


FIGURE 1 | Monthly total rainfall (RF), average minimum and maximum temperatures (Temp.), and relative humidity (RH) in the Bonke and Chencha areas of southern Ethiopia during the cropping seasons of 2020 and 2021.

SC (a.i. = azoxystrobin 200 g L^{-1} + difenoconazole 125 g L^{-1}), Carbonchlor 50% SC (a.i. = carbendazim 25% + chlorothalonil 25%), and Matico (a.i. = metalaxyl 8% + mancozeb 64% WP), which have a systemic nature in their mode of action, were bought from an agrochemical dealer in Ethiopia. The active substances found in Othello-Top are members of the strobilurins (azoxystrobin) and dioxolanes (difenoconazole) chemical classes. Carbonchlor is a combination of the benzimidazoles (carbendazim) and chloronitrile (chlorothalonil) chemical classes, whereas Matico is a combination of the anilide/phenylamide (metalaxyl) and ethylene bisdithiocarbamates (mancozeb) chemical classes. Carbonchlor and Matico fungicides were registered in 2018, while Othello was registered in 2019 for cereal, pulse, root, tuber, and vegetable crops against foliar fungal diseases (MoA 2020). Othello, Carbonchlor, and Matico fungicides are recommended to be applied at a rate of 1 L ha^{-1} with 250 L of water, 2.5 L ha^{-1} with 1000 L of water, and 3 kg ha^{-1} with 800 L of water, respectively. According to the manufacturer, the fungicides are recommended to be sprayed every 10–15 days at 2–3 spray frequencies, depending on disease onset, pressure, and growth stage of the crop.

2.3 | Treatments, Experimental Design, and Field Procedures

There were a total of 24 treatment combinations, which were composed of two cultural practices, three pea varieties, and three fungicides, along with respective unmanaged controls (Table 1). This experiment utilized a split–split plot design with three replicates. Cultural practices, pea varieties, and fungicides were assigned to the main plots, subplots, and sub-subplots, respectively. Individual treatment combinations were assigned at random to study plots within a block. During the study, a well-prepared seedbed, which was tilled 3–4 times based on soil characteristics, was used in the two locations. The total field size was 30.5 m × 47.7 m, with a unit plot size of 2.6 m × 3.0 m (7.8 m^2). Each plot consisted of 15 rows. Spaces between rows and plants were adjusted to 20 and 5 cm, in that order. Plots were separated by 1.5 m, and replications were spaced at 2.5 m to minimize fungicide cross-contamination.

TABLE 1 | Details of treatment combinations employed for the field experiments at Bonke and Chencha in southern Ethiopia during the 2020 and 2021 cropping seasons.

S/N	Treatment combinations
1	Bursa + without staking (control one)
2	Bursa + with staking
3	Bursa + without staking + Carbonchlor
4	Bursa + without staking + Matico
5	Bursa + without staking + Othello-Top
6	Bursa + with staking + Carbonchlor
7	Bursa + with staking + Matico
8	Bursa + with staking + Othello-Top
9	Burqitu + without staking (control one)
10	Burqitu + with staking
11	Burqitu + without staking + Carbonchlor
12	Burqitu + without staking + Matico
13	Burqitu + without staking + Othello-Top
14	Burqitu + with staking + Carbonchlor
15	Burqitu + with staking + Matico
16	Burqitu + with staking + Othello-Top
17	Tegegnech + without staking (control one)
18	Tegegnech + with staking
19	Tegegnech + without staking + Carbonchlor
20	Tegegnech + without staking + Matico
21	Tegegnech + without staking + Othello-Top
22	Tegegnech + with staking + Carbonchlor
23	Tegegnech + with staking + Matico
24	Tegegnech + with staking + Othello-Top

Sowing was done on July 20 and 15 at Bonke and on July 20 and 23 at Chencha in 2020 and 2021, respectively. About 52 plants per row were maintained, and a total of 780 plants per plot were established during the study.

Following recommendations by MoANR and EATA (2018), field fertilization was conducted using NPS blended fertilizer at a rate of 121 kg ha^{-1} for all plots at the time of planting. Fungicide sprays were initiated in response to the first visual PM signs observed on Tegegnech and Burqitu varieties and were repeated every 15 days for three consecutive sprays per site and year. The initial fungicide application was carried out at 40 (2020) and 37 (2021) days after sowing (DAS) at Bonke and 38 (2020) and 41 (2021) DAS at Chencha. Fungicides were sprayed using a manually directed knapsack sprayer, which was adjusted to deliver 500–700 L of water ha^{-1}. Unsprayed and unstaked plots were left for each variety as controls to allow high PM development. Weeding, earthing up, and regular follow-ups were done similarly for all plots, regardless of treatment types.

2.4 | Monitoring of PM

In 2020 and 2021, PM severity was started when typical PM symptoms were observed, which were characterized during the study, and assessed at weekly intervals prior to each fungicide application, commencing at 40 and 37 days after sowing (DAS) at Bonke and 38 and 41 DAS at Chencha, respectively. Disease monitoring was stopped as the majority of planted peas across plots showed senescence and physiological maturity. Disease severity was determined for 20 randomly selected and pretagged plants per row in each plot. It was assessed following a 0–10 rating scale developed by Falloon et al. (1995), where 0 = no disease; 1 = 1%–5% leaflet area with lesions; 2 = 6%–10% leaflet area with lesions; 3 = 11%–15% leaflet area with lesions; 4 = 16%–20% leaflet area with lesions; 5 = 21%–33% leaflet area with lesions and small necrosis visible; 6 = 34%–46% leaflet area with lesions and moderate necrosis visible; 7 = 47%–60% leaflet area with lesions and extensive necrosis; 8 = 61%–73% leaflet area with lesions and extensive necrosis with the start of defoliation; 9 = 74%–86% leaflet area with lesions, more of the leaflet area damaged, and extensive necrosis with collapsed leaflets; and 10 = 87%–100% leaflet area with lesions, defoliation, and death of the leaf. A total of nine assessments were conducted during the epidemic periods for each location and year, and scores were transformed into a percentage disease severity index (PSI) for data analysis (Wheeler 1969).

$$\text{PSI}(\%) = \frac{\text{Sum of all numerical ratings}}{\text{Total number of observations} \times \text{maximum rating scale}} \times 100$$

The area under disease progress curve (AUDPC), representing the cumulative extent of disease impacting either the entire plant or a specific section during epidemic periods, was calculated from disease severity data regressed over time using the formula suggested by 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 n is the total number of disease scores, t_i is the time of the i^{th} disease severity valuation in days from the first assessment date, and x_i is the disease severity at the i^{th} assessment date. The

AUDPC is expressed in %-days because severity (x) is expressed in % and time (t) in days.

2.5 | Assessment of Agronomic Traits, Nodule, and Yield Loss

Agronomic variables, including plant height (PH), number of productive pods per plant (NPP), number of seeds per pod (NSP), hundred seed weight (HSW), and grain yield (GY), were measured in the experiments. PH (cm) was measured from the base of the stem to the tip of 10 randomly selected sample plants at 90% physiological maturity. The NPP was assessed by counting the total number of effective productive pods of sample plants from 20 randomly selected sample plants per plot during crop harvesting. Similarly, the NSP was determined by counting the total NSP from 20 randomly selected pods from 20 sample plants per plot during crop harvesting. Then, each of the mean values for PH (averaged for 10 plants), NPP (averaged for 20 plants), and NSP (averaged for 20 pods) was used for data analysis. At crop senescence or harvestable maturity, GY was recorded from 13 harvestable middle rows per plot in kilograms and then converted to yield in terms of t ha^{-1}. It was conducted at 154 and 150 DAS at Bonke and 150 and 160 DAS at Chencha in the 2020 and 2021 cropping seasons, respectively. Following the procedure described by Taran et al. (1998), GY was corrected to 12% storable moisture content for pulse crops. In addition, HSW (g) per plot was measured from a random sample of 100 seeds from the total harvested yield per plot and adjusted to 12% moisture content for further analysis.

The total number of nodules (TNN) and number of effective nodules (NEN) were assessed at the mid-flowering stage, specifically during the 7th to 9th node stage (70–75 DAS), which corresponds to the R1 stage (flower bud) (Knott 1987). Nodule assessment, whether effective or not, was conducted using five randomly chosen plants from the middle rows of each plot. Assessment was carried out following a destructive sampling method, and TNN and ENN parameters were counted after the roots had been properly cleaned to remove any soil that adhered to them and then rinsed with tap water in a sieve. Harvested nodules were dissected using a surgical blade to determine whether they were effective based on the color they exhibited when cut apart. Nodules that produced pink were regarded as effective, while those that appeared creamy white were deemed ineffective (Dobert and Blevins 1993). TNN refers to the sum of effective plus ineffective nodules harvested from selected sampled plants per plot.

The relative yield loss (RYL) of field pea due to PM pressure and associated damage was assessed for each of NPP, NSP, HSW, and GY percentage yield reductions of the less protected plots in relation to the maximally protected plots for all tested combinations of cultural practices, varieties, and fungicides across locations over the cropping years by adopting analogies from Bitew et al. (2022) and Mengesha et al. (2025), employing the following formula:

$$RYL\,(\%) = \frac{Y_{mt} - Y_{lt}}{Y_{mt}} \times 100$$

where Ymt = mean parameter (for NPP, NSP, HSW, or GY) of the best performing treatment combination in the study (maximum protected plot) and Ylt = mean parameter (for NPP, NSP, HSW, or GY) of the other treatments (low- to medium-protected plots). Yield increase over control plots was computed from the change in grain yield between managed and unmanaged plots and expressed in %, as indicated by Bitew et al. (2022) and Mengesha et al. (2025).

2.6 | Data Analyses

Disease, nodulation, and agronomic data were analyzed using analysis of variance (ANOVA) via PROC GLM with the MIXED model in SAS version 9.3 (SAS 2014). In the model, treatments and locations were fixed factors, while cropping years and all interactions, such as blocks, replications, and errors were treated as random factors. Bartlett's chi-square test (Bartlett 1937) was conducted, because the study locations and cropping years were regarded as different environments. Accordingly, ANOVA for the study parameters was performed separately for each location due to the heterogeneity of error variance across locations, whereas a combined ANOVA was employed for cropping years, as error variances for the majority of the study parameters over the 2 years within each location were homogeneous. Duncan's multiple range test (DMRT) was used to separate the means if there were significant variations between and among the treatments at a 5% significance level (Gomez and Gomez 1984). Pearson correlation analyses were conducted to explore the relationships between and among epidemiological components, agronomic traits, and nodule parameters. Moreover, an integral model, which assumes disease damage is proportional to the amount of host tissue infected and the duration of the epidemic period, was used to plot yield data versus AUDPC values to predict yield loss at each stage of disease development following Van der Plank (1963) and Savary et al. (2006) procedures.

2.7 | Analyses of Economic Feasibility

Economic feasibility for the integrated management methods was computed using mean data from both cropping years for each location by employing a CIMMYT (1988) procedures. The net return (NR) and benefit–cost ratio (BCR) were taken into account for the economic return analysis. The NR was obtained by considering the changes in total input costs (TICs), which included expenses for fungicides, the knapsack sprayer, operating labor for application, staking, weeding, harvesting, and land rent, along with the gross return derived from the market price multiplied by GY. The BCR, determined by the ratio of the NR to the TICs, serves as a metric that demonstrates the relationship between the relative costs and the benefits obtained. A feasibility study was performed based on the actual cost of input variables and the GY market price in each location per year. The mean unit prices of GY per kg during the cropping years of 2020 ($0.81 and $0.91) and 2021 ($0.72 and $0.80) were $0.76 and $0.85, respectively. These prices were calculated using the exchange rates of $1 to Ethiopian birr (ETB) 39.37 in 2020 and $1 to ETB 49.99 in 2021 at the time of marketing. The actual GY decreased by 10% to account

for the difference between the yield expected from experimental and farmer fields from the same treatment. All expenses and income values were transformed to a per-hectare basis for the analysis.

3 | Results

3.1 | ANOVA for Study Parameters

Combined ANOVA over locations and years discovered variable degrees of significant variation ($p < 0.0001$ to < 0.05) in mean squares for study parameters between and among the main plot (F-value = 25.31–1521.46), subplot (F-value = 2.51–388.43), and sub-subplot (F-value = 11.92–3024.20) factors (Table 2). This implies there were differences in the effects of evaluated treatments on PM metrics, agronomic traits, and nodulation across locations and years. However, there was nonsignificant ($p > 0.05$) variation in the interactions of cultural practice with variety and location with year for the mean square of any disease metrics, agronomic traits, and nodulation (Table 2). Thus, PM development, agronomic attributes, and nodulation appeared to be insensitive to cultural practices, variety resistance levels, and environmental variations, indicating invariable responses to treatment effects over locations and years. Although the interactions between cultural practice and variety, as well as between location and year, are nonsignificant in the combined ANOVA, most study parameters showed significant results ($p < 0.0001$ to < 0.05) in the mean square of the interaction among location, cropping year, cultural practice, variety, and fungicide application within the sub-subplot factors (Table 2). These suggest that there was considerable distinction among treatments across locations and years. Also, the interplay of location, years, cultural practice, variety, and fungicide had a significant impact on treatment comparisons for selecting effective combined approaches for managing PM, boosting agronomic performance, and influencing nodule formation across locations.

3.2 | PM Epidemics

3.2.1 | Disease Severity

While characteristic signs of PM were noted during the early growth stage, with an average of 39 DAS across locations and years, the disease became more prominent at later growth stages of field pea (Figure 2). Signs were observed on leaves, stems, flower buds, and pods, with characteristic features of white to grayish powdery patches and purple blotches on the upper and lower surfaces of leaves and flower buds, powdery patches on stems and pods, and tiny, black, spherical structures (cleistothecia) on lower leaves (Figure 2a–c). Severely affected leaves and stems exhibited yellow or brown discoloration, defoliation, collapse, and premature death (Figure 2d). However, cultural practices, variety, and fungicide spray integrations significantly ($p < 0.0001$, F-value = 5.86–23.30) reduced further symptomatic development, particularly starting from the sixth disease assessment date, across locations in both years (Table 3).

Over time, PM severity was higher in Bonke (16.58%–23.84%) than in Chencha (17.36%–21.51%). Among treatments, severity

TABLE 2 | Combined analysis of variance for mean squares of disease components and agronomic traits of field pea at Bonke and Chencha in southern Ethiopia during 2020 and 2021 main cropping seasons.

Source of variation	df	Disease severity (%)				Growth, yield, and yield-related traits of field pea					Nodule development	
		PSI7	PSI8	PSI9	AUDPC (%-day)	PH	NPP	NSP	HSW	GY	TNN	NEN
Main/whole plot factors												
Block (within LOC and YR)	8	57^{ns}	45^{ns}	41^{ns}	$44{,}212^{ns}$	2202*	11^{ns}	1.02^{ns}	2.86^{ns}	1.72^{ns}	724^{ns}	362^{ns}
Location (LOC)	1	4624****	7509****	7977****	2.7×10^{5}****	12,500****	46^{ns}	633****	105*	36****	59,676***	20,139*
Year (YR)	1	15.51***	27.12^{ns}	25.22^{ns}	551,909****	40,338****	23.1^{ns}	754^{ns}	12.77^{ns}	3.75*	122^{ns}	25.94^{ns}
Cultural practices (CP)	1	1805****	2520****	2177****	485,512****	14,3063****	225****	2414****	3918****	115****	29,023*	14,049*
Error (within LOC and YR)	8	56.30	65.76	66.30	17,041	649.59	14.03	21.48	19.89	0.79	4801	3097
F-value ($\alpha = 0.05$)		106.36	124.94	98.33	1521.46	1049.70	25.31	133.96	168.66	59.90	188.80	132.84
Subplot factors												
Variety (VAR)	2	607****	838****	918****	17,2773****	17,073****	356****	296****	255****	4.13**	59,709****	95,929****
CP*VAR	2	116^{ns}	1.06^{ns}	88.59^{ns}	$17{,}515^{ns}$	315.40^{ns}	2.56^{ns}	3.27^{ns}	0.97^{ns}	4.13*	3501^{ns}	2102^{ns}

(Continues)

TABLE 2 | (Continued)

Source of variation	df	Disease severity (%)			AUDPC (%-day)	Growth, yield, and yield-related traits of field pea					Nodule development	
		PSI7	PSI8	PSI9		PH	NPP	NSP	HSW	GY	TNN	NEN
Error (within LOC and YR)	32	52.23	60.40	61.11	16,580.08	533.63	8.93	17.12	13.29	0.77	4331.21	2362.44
F-value ($\alpha = 0.05$)		35.77	41.55	41.46	541.42	125.27	40.04	16.43	10.98	2.15	388.43	907.04
Sub-subplot factors												
Fungicide (FUN)	3	3361****	3843****	4023****	965,054****	11,085****	202****	508****	277****	38****	330,219****	172,523**
CP*FUS	3	217****	275****	138***	551,909****	40,338****	2.49^{ns}	16.09^{ns}	7.64^{ns}	6.4****	8093.7****	4234****
VAR*FUS	6	56.6****	63.2****	58.6****	11,857.14*	1110.16*	12.08^{ns}	6.28^{ns}	36.60**	0.10^{ns}	14413****	12576****
LOC*YR	1	44^{ns}	327*	389*	25054^{ns}	1680^{ns}	86*	41^{ns}	7.96^{ns}	1.33^{ns}	14,404^{ns}	4679^{ns}
CP*VAR*FUN	6	34.86**	53.9****	22.13ns	4137.94^{ns}	54.57^{ns}	0.22^{ns}	0.97^{ns}	0.85^{ns}	0.23^{ns}	1418****	730.9****
LOC*CP*VAR	2	0.35^{ns}	1.98^{ns}	3.88^{ns}	886.03^{ns}	143.64^{ns}	2.57^{ns}	14.76^{ns}	5.71^{ns}	1.56^{ns}	3.67^{ns}	0.60^{ns}
YR*CP*VAR	2	2.60^{ns}	5.68^{ns}	1.58^{ns}	434.64^{ns}	50.56^{ns}	2.72^{ns}	3.51^{ns}	9.21^{ns}	0.59^{ns}	0.16^{ns}	0.01^{ns}
YR*LOC*VAR	2	4.05^{ns}	13.32^{ns}	30.60^{ns}	904.60^{ns}	1306.96^{ns}	12.70^{ns}	69.92*	144****	0.10^{ns}	6.85^{ns}	14.60^{ns}
LOC*CP*FUN	3	3.31^{ns}	8.13^{ns}	8.85^{ns}	1277.17^{ns}	7.13^{ns}	0.05^{ns}	2.48^{ns}	0.43^{ns}	0.20^{ns}	14.81^{ns}	6.03^{ns}
YR*CP*FUN	3	28.35*	5.75^{ns}	6.46^{ns}	307.35^{ns}	80.54^{ns}	1.19^{ns}	1.30^{ns}	0.13^{ns}	0.51^{ns}	0.09^{ns}	0.07^{ns}
LOC*VAR*FUN	6	7.92^{ns}	16.79^{ns}	2316^{ns}	2429.04^{ns}	104.67^{ns}	9.49^{ns}	14.08^{ns}	15.0^{ns}	0.21^{ns}	2.70^{ns}	2.26^{ns}
YR*LOC*FUN	3	22.58^{ns}	21.34^{ns}	14.60^{ns}	25,342.49^{ns}	69.38^{ns}	1.83^{ns}	22.16^{ns}	29.16*	0.64^{ns}	2766****	1004****
YR*VAR*FUS	6	3.88^{ns}	9.66^{ns}	6.18^{ns}	4874.92^{ns}	149.24^{ns}	14.45^{ns}	13.47^{ns}	58.3****	0.15^{ns}	0.98^{ns}	0.50^{ns}
LOC*CP*VAR*FUN	6	1551^{ns}	9.96^{ns}	13.54^{ns}	3301.83^{ns}	540.28^{ns}	20.4***	39.3****	26.36***	0.59**	102.56^{ns}	35.35^{ns}
YR*CP*VAR*FUN	6	4625****	12.13^{ns}	10.93^{ns}	385,069^{ns}	521.67^{ns}	223****	8.80^{ns}	51.5****	0.54*	2.27^{ns}	1.28^{ns}
LOC*YR*CP*VAR*FUN	6	13.01^{ns}	22.87**	25.69**	5186.97****	207.21^{ns}	4.10**	11.81^{ns}	19.2****	0.66**	294.59***	142.95*
Error (within LOC and YR)	192	10.38	11.95	13.06	5087.79	403.19	6.84	11.52	9.79	0.28	144.17	65.84
F-value ($\alpha = 0.05$)		198.06	190.53	181.71	3024.20	81.33	22.72	28.19	11.92	19.79	2148.19	1631.27
Ground mean		16.97	20.17	22.14	319.11	136.29	8.89	18.02	23.23	1.92	153.72	105.76
CV (%) (main plot factors)		44.21	40.20	35.91	40.91	18.70	42.15	25.71	19.20	46.36	45.08	52.62
CV (%) (subplot factors)		42.58	38.53	34.47	40.35	16.95	33.63	22.96	16.27	45.62	42.81	45.96
CV (%) (sub-subplot factors)		18.98	17.14	15.93	22.35	14.73	29.43	18.83	13.47	27.50	7.81	7.67

Note: PSI7–PSI9 refer to percentage disease severity index at the last three dates of disease assessments. ns = not significant at $p < 0.05$.
Abbreviations: AUDPC = area under disease progress curve; CV = coefficient of variation (%); df = degrees of freedom; GY = grain yield (t ha^{-1}); HSW (g) = hundred seed weight measured in gram; NEN = number of effective nodules; NPP = number of productive pods per plant; NSP = number of seed per plant; PH = plant height (cm); TNN = total number of nodules.
*Significant difference at $p < 0.05$.
**Significant difference at $p < 0.01$.
***Significant difference at $p < 0.001$.
****Significant difference at $p < 0.0001$.

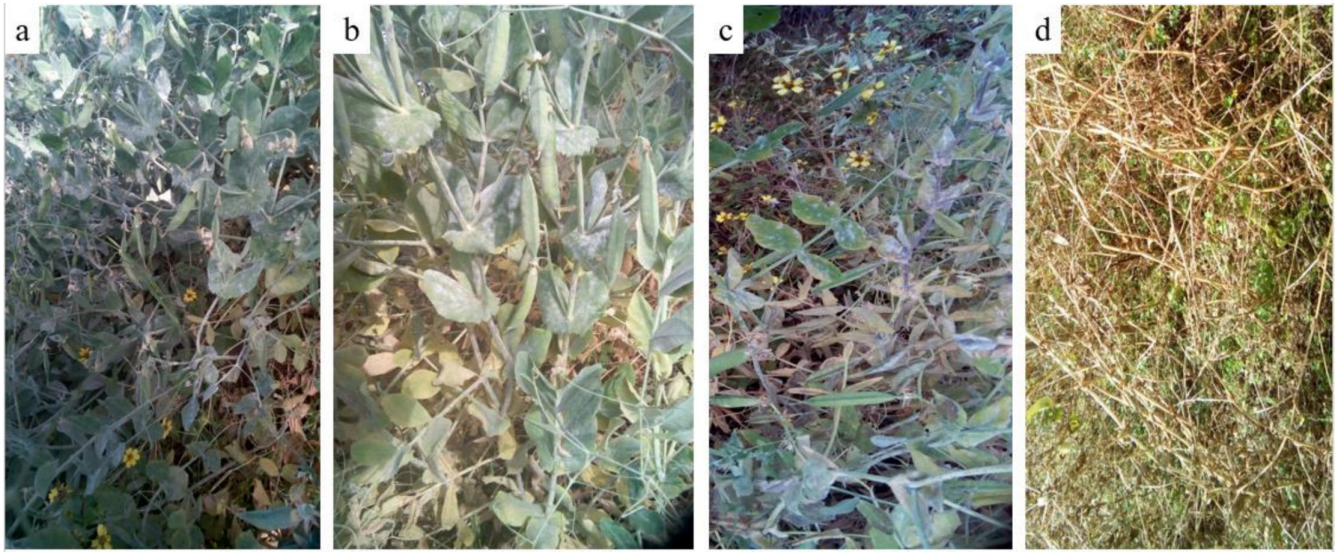


FIGURE 2 | Characteristic signs of field pea powdery mildew caused by *Erysiphe pisi* at experimental sites. (a, b) Characteristic sign appears as white to grayish, powdery patches, and purple blotches on the upper and lower surfaces of leaves, powdery patches on stems and pods, and tiny, black, and spherical structures (cleistothecia) on lower leaves on the variety Burqitu and Tegegnech supported with staking, respectively. (c) Typical signs consist of white to gray powdery patches and purple blotches on leaves, powdery patches on stems and pods, and tiny black cleistothecia on lower leaves of Tegegnech variety without staking. (d) Severely affected leaves and stems that turned yellow or brownish, defoliated, collapsed, and prematurely died from the variety Burqitu without staking.

levels recorded in plots treated with the Bursa variety, staking, and Othello fungicide spray were as low as 5.50%, 8.69%, and 10.01% at Bonke and 7.59%, 8.85%, and 11.74% at Chencha in the last three assessment times. Additionally, integrations of the Bursa variety with staking and Othello fungicide spray lowered disease severity by 68.27% and 62.84% at Bonke and 56.05% and 49.72% at Chencha compared with unmanaged plots and plots that received staking but without fungicide spray, respectively, at the final date of disease assessment in the 2 years (Table 3). Nonetheless, Othello fungicide-sprayed plots of each variety with no staking had significantly lower disease severity than other plots with and without fungicide and staking late in the epidemic periods across locations over the years (Table 3). Results also showed that plots managed with staking but without fungicide spraying had reduced severity compared to plots left unstaked and unsprayed for each variety at both locations over time. Over the epidemic periods, the Burqitu variety without staking and fungicide spray showed the highest severity, which ranged from 36.29% (PSI7) to 46.20% (PSI9) across locations, although statistically on par with the variety Tegegnech, which had the same treatment, at Bonke (Table 3).

3.2.2 | AUDPC

Noticeable variations ($p < 0.0001$, F-value = 9.15–9.26) were observed among integrations of cultural practices, varieties, and fungicide applications for AUDPC values in both locations over the 2 years (Figure 3). Mean AUDPC values were higher at Bonke (328.44%-days) than at Chencha (309.70%-days). Accordingly, field pea sowing at Bonke incurred 5.68% more disease damage than at Chencha. The Bursa variety with staking and Othello fungicide spray had the lowest AUDPC values of 112.45%-days at Bonke and 151.26%-days at Chencha compared to other treatments in both cropping seasons. In both locations and years, the Burqitu variety, when not staked and without applied fungicide, showed the highest mean AUDPC values. These values were statistically similar to those of the Burqitu and Tegegnech varieties that were treated with Matico fungicide and not staked at Bonke, as well as to the Tegegnech variety with and without staking at Chencha (Figure 3). Evidently, fungicide-sprayed plots of each variety, irrespective of staking practices, resulted in lower AUDPC than their counterpart control plots. Specifically, planting Bursa, Burqitu, and Tegegnech, along with staking practices and Othello fungicide spray, reduced AUDPC by 73.61%, 72.76%, and 69.37% at Bonke and 61.93%, 66.06%, and 64.00% at Chencha compared with their corresponding control plots, respectively (Figure 3).

3.3 | Performance of Agronomic Traits

There were significant differences ($p < 0.0001$, F-value = 4.32–22.93) in agronomic traits among treatments across locations and years (Table 4). In both locations and years, the integration of the Burqitu variety with staking and Othello fungicide spray had the tallest mean PH, which was statistically similar to plots treated with staking and Matico fungicide at Bonke and 25% of the treatments at Chencha. Over time, planting the Burqitu variety with staking and Othello fungicide resulted in the highest mean NPP and NSP at Bonke, while the Tegegnech variety with the same treatment recorded the highest NPP and NSP at Chencha. The lowest mean PH, NPP, and NSP were recorded from plots left without staking and fungicide spraying on the Tegegnech variety, followed by Bursa and Burqitu varieties at Bonke, and the Bursa, Tegegnech, and Burqitu varieties at Chencha, in that order of presentation. Trends followed similar patterns when plots were treated with staking alone, with no

TABLE 3 | Interaction effects of staking, variety, and fungicide spray on powdery mildew epidemic in field pea at Bonke and Chencha in southern Ethiopia during the 2020 and 2021 main cropping seasons.

Treatment combination			Disease severity (%), Bonke			Disease severity (%), Chencha		
Variety	Cultural practice	Fungicide	PSI7	PSI8	PSI9	PSI7	PSI8	PSI9
Tegegnech	Without staking	Unsprayed	32.30^{ab}	37.50^{ab}	37.90^{ab}	30.89^{b}	33.31^{b}	34.29^{b}
		Carbonchlor	15.07^{d-j}	20.33^{c-g}	23.43^{c-g}	16.20^{d-g}	17.93^{f-i}	19.40^{f-h}
		Matico	20.35^{c-g}	25.95^{b-e}	27.58^{b-e}	19.88^{cd}	21.15^{d-f}	24.92^{c-e}
		Othello	9.99^{g-j}	13.57^{e-g}	16.56^{e-h}	11.48^{g-k}	12.78^{i-l}	15.39^{h-j}
	With staking	Unsprayed	23.87^{b-d}	26.57^{b-e}	28.61^{b-e}	22.68^{c}	26.37^{c}	27.96^{cd}
		Carbonchlor	12.16^{e-i}	16.39^{d-g}	18.89^{d-h}	13.26^{d-f}	14.40^{h-k}	15.86^{g-j}
		Matico	16.14^{d-i}	20.79^{c-g}	23.50^{c-g}	16.73^{f-j}	17.79^{f-i}	19.77^{f-h}
		Othello	8.34^{h-j}	11.33^{fg}	13.83^{f-h}	9.54^{i-k}	10.62^{kl}	12.80^{ij}
Burqitu	Without staking	Unsprayed	36.29^{a}	41.74^{a}	42.76^{a}	38.45^{a}	44.89^{a}	46.20^{a}
		Carbonchlor	16.78^{c-i}	22.36^{c-f}	26.07^{b-g}	18.66^{c-e}	20.06^{d-g}	22.74^{d-f}
		Matico	23.42^{b-d}	26.85^{b-e}	30.29^{a-d}	22.57^{c}	23.95^{d-e}	27.22^{c-e}
		Othello	11.31^{e-i}	16.83^{d-g}	19.36^{d-h}	13.20^{f-j}	14.79^{g-k}	17.07^{f-j}
	With staking	Unsprayed	26.88^{bc}	31.50^{a-c}	33.54^{a-c}	22.53^{c}	25.24^{cd}	29.81^{bc}
		Carbonchlor	12.99^{d-i}	17.42^{d-g}	20.37^{c-g}	14.12^{e-i}	15.34^{g-k}	17.60^{f-j}
		Matico	17.21^{c-i}	21.71^{c-g}	26.24^{b-g}	17.96^{c-f}	19.28^{e-h}	21.65^{e-g}
		Othello	9.13^{h-j}	13.76^{e-g}	15.89^{e-h}	10.86^{h-k}	12.17^{kl}	14.04^{h-i}
Bursa	Without staking	Unsprayed	21.83^{c-e}	27.50^{b-d}	31.55^{a-d}	22.46^{c}	24.04^{c-e}	26.71^{c-e}
		Carbonchlor	13.21^{d-j}	17.69^{d-g}	20.07^{d-h}	14.20^{e-i}	15.63^{g-k}	18.03^{f-i}
		Matico	16.78^{c-i}	22.61^{c-f}	25.42^{b-g}	18.71^{c-e}	19.90^{e-g}	22.26^{d-f}
		Othello	7.69^{ij}	11.43^{e-g}	12.98^{gh}	8.93^{f-j}	10.43^{kl}	13.85^{h-j}
	With staking	Unsprayed	18.62^{c-h}	23.46^{c-f}	26.94^{b-f}	18.54^{c-e}	20.03^{d-g}	23.35^{d-f}
		Carbonchlor	11.05^{f-i}	14.80^{d-g}	17.08^{e-h}	11.83^{g-k}	13.02^{i-l}	15.03^{h-j}
		Matico	14.05^{d-j}	18.93^{c-g}	21.29^{c-h}	15.45^{d-g}	16.58^{f-j}	18.62^{f-i}
		Othello	5.50^{j}	8.69^{g}	10.01^{h}	7.59^{k}	8.85^{l}	11.74^{j}
Grand mean			16.58	21.24	23.84	17.36	19.11	21.51
Pooled error			59.29	53.19	46.81	13.29	16.41	19.46
F-value ($\alpha = 0.05$)			5.86	7.37	8.29	22.43	23.30	19.07
p-values			< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
CV (%)			46.44	34.34	28.70	20.99	21.20	20.43

Abbreviation: CV = coefficient of variation (%).
PSI7, PSI8 and PSI9 denotes to mean percentage disease severity index at the last-three dates of assessments in the study locations during the two cropping years.
Means within a column followed by the same letter(s) are not statistically significant at $p < 0.05$.

fungicide spray for all pea varieties across locations and years (Table 4).

Likewise, combined implementations of the variety Burqitu with staking and Othello fungicide improved mean HSW, though statistically on par with about 45.83% of the treatments at Bonke over the years. At Chencha, plots with the Bursa variety, staking, and Othello fungicide had the highest mean HSW, which did not differ significantly from plots with the Burqitu variety, staking, and Matico fungicide spray (Table 4). Across treatments, integrations of staking and Othello fungicide enhanced HSW by 40.81% (Bursa), 38.79% (Burqitu), and 35.70% (Tegegnech) at Bonke over the years. A related trend was observed at Chencha in the 2 years. Regarding GY, integrations of the variety Burqitu with staking and Othello fungicide provided a higher GY than any other treatment

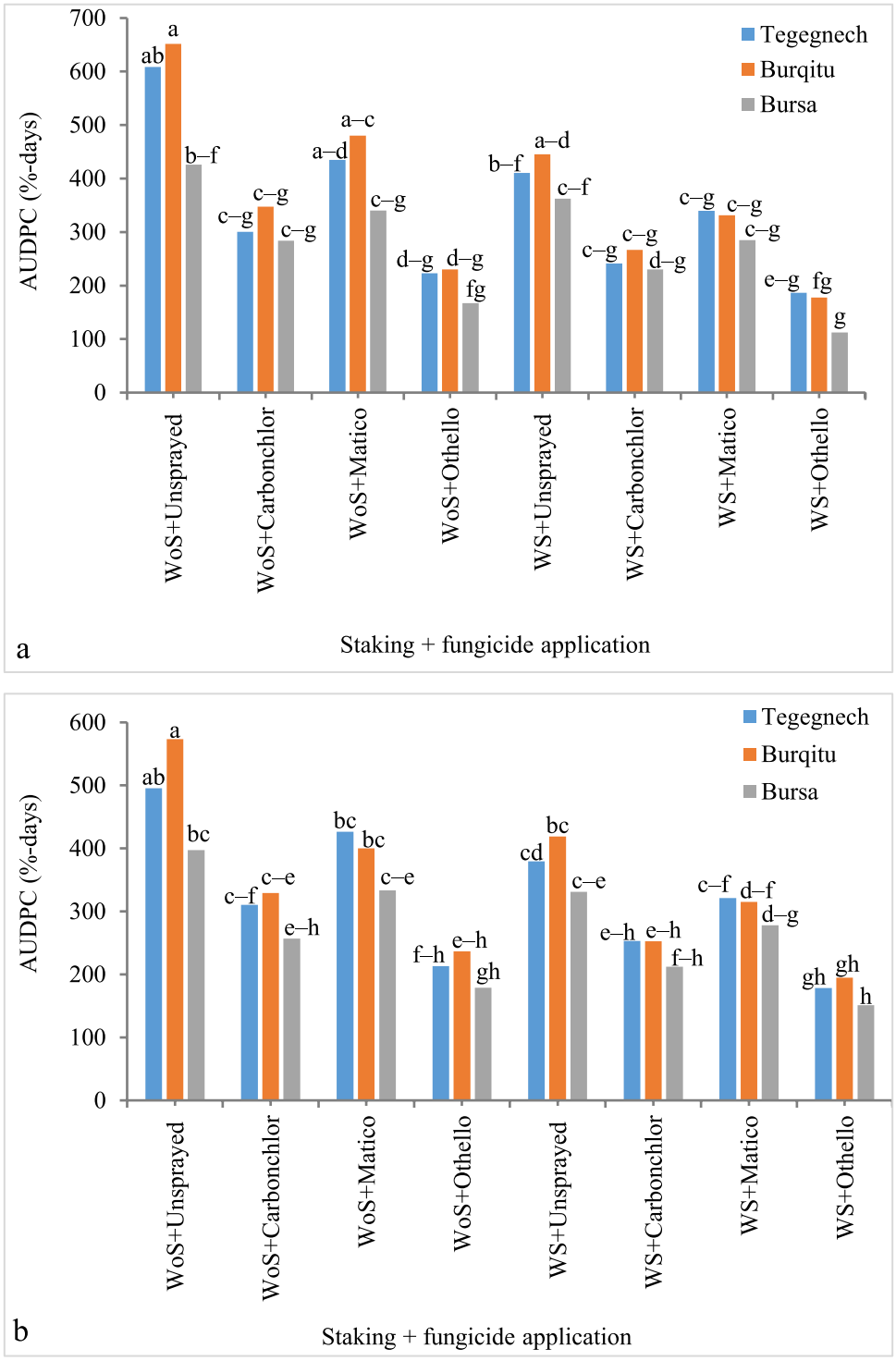


FIGURE 3 | Area under disease progress curves (AUDPC) of field pea powdery mildew as influenced by combined operations of staking, varieties, and fungicide application at Bonke (a) and Chencha (b) in southern Ethiopia during the 2020 and 2021 main cropping seasons. *Note:* WoS = without staking; WS = with staking.

combinations at Bonke over the years. At Chencha, a larger mean GY was obtained from plots treated with combinations of the variety Tegegnech, staking, and Othello fungicide in the cropping years. Overall findings demonstrated that integrated operations that engaged the variety, staking, and Othello fungicide spray were found to have higher synergistic impacts in improving agronomic traits than other treatments across locations over the 2 years (Table 4).

3.4 | Effects of Combined Measures on Nodule Development

Field pea varieties, whether staked or not, supported with fungicide spraying, exhibited significantly ($p < 0.0001$, F-value = 64.46–67.80 for TNN and 109.95–116.90 for NEN) variable nodule development (Figure 4). Although integrations of each variety with staking and fungicide spraying had significant effects on

TABLE 4 | Combined effects of staking, variety, and fungicide application on agronomic performance of field pea at Bonke and Chencha in southern Ethiopia during the 2020 and 2021 main cropping seasons.

Treatment combination			Bonke					Chencha				
Variety	Cultural practice	Fungicide	PH (cm)	NPP	NSP	HSW (g)	GY (t ha^{-1})	PH (cm)	NPP	NSP	HSW (g)	GY (t ha^{-1})
Tegegnech	Without staking	Unsprayed	86.43^{j}	5.36^{g}	9.73^{i}	15.96^{g}	0.77^{ij}	107.37$^{g–i}$	5.75^{ef}	13.81^{fg}	16.58^{i}	0.63^{k}
		Carbonchlor	96.11^{ij}	6.44^{fg}	12.11^{hi}	18.29^{fg}	1.43$^{f–j}$	114.91$^{f–i}$	7.44$^{c–f}$	16.14$^{e–g}$	17.86^{hi}	1.15$^{h–k}$
		Matico	103.35$^{h–j}$	6.95^{fg}	13.84$^{f–i}$	19.26$^{e–g}$	1.56$^{f–i}$	118.04$^{f–i}$	7.95$^{c–f}$	17.19$^{d–g}$	19.48$^{f–i}$	1.55$^{f–j}$
		Othello	111.71$^{g–j}$	8.40$^{e–g}$	15.32$^{e–i}$	18.08^{fg}	1.84$^{d–h}$	129.12$^{d–i}$	10.28$^{a–c}$	18.43$^{c–g}$	19.12$^{g–i}$	1.78$^{f–i}$
	With staking	Unsprayed	122.41$^{e–i}$	6.58^{fg}	13.54$^{f–i}$	21.73$^{c–g}$	1.22$^{g–j}$	147.34$^{c–f}$	7.04$^{c–f}$	19.17$^{b–f}$	23.03$^{d–h}$	1.67$^{f–j}$
		Carbonchlor	134.09$^{d–h}$	7.89$^{e–g}$	16.88$^{d–h}$	25.02$^{a–f}$	1.83$^{d–h}$	159.66$^{a–e}$	9.11$^{b–e}$	22.41$^{a–d}$	24.83$^{c–e}$	2.51$^{d–f}$
		Matico	144.31$^{c–f}$	8.52$^{e–g}$	19.31$^{c–f}$	26.38$^{a–e}$	2.14$^{c–g}$	164.01$^{a–d}$	9.74$^{a–d}$	23.88$^{a–c}$	27.10$^{b–d}$	3.34$^{b–d}$
		Othello	156.05$^{b–d}$	10.32$^{d–f}$	21.37$^{b–d}$	24.82$^{a–f}$	2.91^{bc}	179.32$^{a–c}$	12.57^{a}	25.60^{a}	26.60^{cd}	4.36^{a}
Burqitu	Without staking	Unsprayed	106.15$^{g–j}$	9.00$^{d–g}$	12.83$^{g–i}$	19.16$^{e–g}$	0.88^{ij}	114.25$^{f–i}$	6.64$^{d–f}$	14.02^{fg}	16.71^{i}	1.03$^{h–k}$
		Carbonchlor	117.95$^{e–j}$	10.94$^{c–f}$	18.58$^{c–g}$	22.16$^{c–g}$	1.45$^{f–j}$	124.91$^{e–i}$	8.09$^{c–f}$	15.90$^{e–g}$	18.75$^{g–i}$	1.19$^{h–k}$
		Matico	132.50$^{d–h}$	12.30$^{b–e}$	18.66$^{c–f}$	21.64$^{c–g}$	1.58$^{f–i}$	133.79$^{d–i}$	7.85$^{c–f}$	15.86$^{e–g}$	18.05$^{g–i}$	1.36$^{h–k}$
		Othello	148.71$^{c–e}$	15.35^{ab}	21.75$^{b–d}$	23.08$^{b–g}$	1.90$^{d–h}$	139.81$^{d–g}$	9.85$^{b–d}$	17.64$^{d–g}$	18.81$^{g–i}$	1.78$^{f–i}$
	With staking	Unsprayed	148.04$^{c–e}$	10.97$^{c–f}$	17.85$^{c–h}$	26.05$^{a–e}$	1.40$^{f–j}$	159.24$^{a–e}$	8.17$^{c–f}$	19.48$^{b–f}$	23.23$^{d–g}$	1.63$^{f–j}$
		Carbonchlor	164.57$^{b–d}$	13.40$^{b–d}$	25.91^{ab}	30.23^{a}	2.60$^{b–d}$	163.13$^{a–d}$	8.97$^{b–f}$	18.61$^{c–g}$	25.22$^{c–e}$	2.40$^{d–g}$
		Matico	185.02^{ab}	15.03$^{a–c}$	26.05^{ab}	29.42^{ab}	3.22^{b}	186.19^{ab}	9.68$^{a–d}$	22.05$^{a–d}$	25.15$^{c–e}$	3.23^{cd}
		Othello	207.50^{a}	18.80^{a}	30.30^{a}	31.30^{a}	4.24^{a}	194.48^{a}	12.13^{ab}	24.56^{ab}	26.23^{cd}	4.21^{ab}
Bursa	Without staking	Unsprayed	95.62^{ij}	6.31f^{g}	10.62^{i}	18.07^{fg}	0.64^{j}	98.47^{i}	5.51^{f}	12.79^{g}	17.42^{i}	0.46^{k}
		Carbonchlor	105.09$^{h–j}$	5.28^{g}	12.52^{hi}	19.39$^{d–g}$	1.05$^{h–j}$	100.86^{hi}	6.08^{ef}	14.13^{fg}	20.59$^{e–i}$	0.97$^{i–k}$
		Matico	119.51$^{e–i}$	6.99^{fg}	14.28$^{e–i}$	19.98$^{d–g}$	1.40$^{f–j}$	113.72$^{f–i}$	7.56$^{c–f}$	14.45$^{e–g}$	22.77$^{d–h}$	1.46$^{g–k}$
		Othello	115.29$^{f–j}$	8.39$^{e–g}$	16.59$^{d–h}$	22.18$^{c–g}$	1.62$^{e–i}$	102.32^{hi}	7.33$^{c–f}$	15.91$^{e–g}$	25.74$^{c–e}$	1.49$^{f–j}$
	With staking	Unsprayed	137.98$^{c–g}$	7.78$^{e–g}$	14.83$^{e–i}$	24.78$^{a–f}$	1.00$^{h–j}$	137.01$^{d–h}$	6.75$^{d–f}$	17.76$^{d–g}$	24.22$^{c–f}$	1.05$^{h–k}$
		Carbonchlor	146.57$^{c–f}$	6.46$^{f–h}$	17.48$^{d–h}$	26.60$^{a–d}$	2.18$^{c–f}$	140.34$^{d–g}$	7.46$^{c–f}$	19.65$^{b–f}$	28.68^{bc}	2.05$^{e–h}$
		Matico	166.89^{bc}	8.59$^{e–g}$	19.95$^{c–e}$	27.52$^{a–c}$	2.51$^{b–e}$	158.22$^{b–e}$	9.26$^{b–e}$	20.11$^{a–e}$	31.68^{ab}	2.79$^{c–e}$
		Othello	161.09$^{b–d}$	10.32$^{d–f}$	23.20^{bc}	30.53^{a}	3.13^{b}	142.36$^{d–g}$	9.00$^{b–e}$	22.13$^{a–d}$	35.78^{a}	3.64$^{a–c}$
Grand mean			133.87	9.43	17.65	23.40	1.85	138.70	8.34	18.40	23.07	1.99

(Continues)

TABLE 4 | (Continued)

Treatment combination			Bonke				Chencha			
Variety	Cultural practice	Fungicide	PH (cm)	NPP	NSP	HSW (g)	GY (t ha^{-1})	PH (cm)	NPP	NSP	HSW (g)	GY (t ha^{-1})
Pooled error			565.27	5.96	17.84	27.54	0.25	739.51	6.30	18.17	15.08	0.31
F-value ($\alpha = 0.05$)			9.74	12.03	9.07	4.32	18.64	6.16	3.10	4.33	9.78	22.93
p-values			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
CV (%)			17.76	25.88	23.93	22.42	26.95	19.61	30.10	23.16	16.83	28.11

Note: Means within a column followed by the same letter(s) are not statistically significant at $p < 0.05$.
Abbreviations: CV = coefficient of variation (%); GY = grain yield; HSW = hundred seed weight; NEN = number of effective nodules; NPP = number of productive pods per plant; NSP = number of seeds per pod; PH = plant height; TNN = total number of nodules.

reducing disease pressure and improving agronomic characters, applications of fungicides remarkably retarded nodulation across locations and years. Nonetheless, the highest mean TNN and NEN were noted from planting the variety Burqitu, followed by Tegegnech and Bursa, combined with staking practices across locations and over the years. Unmanaged control plots, which involved neither staking nor fungicide application, also showed superior nodules compared to fungicide-treated plots of the same varieties across locations and years. The lowest mean TNN and NEN were recorded from plots treated with Othello fungicide, followed by Carbonchlor and Matico spraying in both locations and years. In this regard, Othello, Matico, and Carbonchlor sprays reduced TNN approximately by 69.26%, 54.91%, and 45.34% and NEN by 70.15%, 56.35%, and 45.34% in the Burqitu variety, respectively, compared to plots maintained with staking for the same variety across locations and in the 2 years. Comparable trends were also noted in other varieties for each fungicide spray (Figure 4).

3.5 | RYL and Yield Advantage

RYL estimations for control plots showed NPP, NSP, and HSW losses ranged from 17.44% to 54.26%, 6.72% to 54.47%, and 5.15% to 39.50% for Tegegnech; 18.35% to 52.13%, 10.22% to 57.66%, and 3.42% to 38.79% for Burqitu; and 16.76% to 48.84%, 9.13% to 42%, and 9.86% to 51.31% for Bursa, compared with highly protected plots across locations over the years, respectively (Table 5). Plots without staking and fungicide spray recorded the largest yield penalties for Tegegnech (73.72%), Burqitu (79.72%), and Bursa varieties (79.55%) at Bonke; and 85.35% (Tegegnech), 75.53% (Burqitu), and 87.36% (Bursa) at Chencha. In this study, the combined implementation of staking and Othello fungicide reduced RYL by 37.20% (Tegegnech), 48.24% (Bursa), and 54.95% (Burqitu) compared with plots treated with the same fungicide but without staking at Bonke. Even more, all varieties tested with Othello fungicide, regardless of staking practices, showed the lowest RYL compared to plots treated with Carbonchlor and Matico across locations and in the 2 years (Table 5). With respect to yield gain/increase, the combined implementation of staking and Othello fungicide increased grain yield gain by 280.52%, 381.82%, and 389.06% at Bonke and 582.81%, 308.74%, and 691.30% at Chencha for Tegegnech, Burqitu, and Bursa varieties over unmanaged plots (no staking and fungicide unsprayed) of each variety, respectively (Table 5).

3.6 | Association of Study Parameters

Different magnitudes of associations were observed between and among epidemiological, agronomic, and nodule parameters across locations over the years (Table 6). At Chencha, AUDPC values were significantly ($p < 0.0001$) and positively correlated with DSI7 ($r = 0.97$), DSI8 ($r = 0.98$), PSI9 ($r = 0.97$), and DPR ($r = 0.32$). Similarly, a significant ($p < 0.001$) correlation and a strong positive association were detected between the TNN and NEN ($r = 0.98$), AUDPC and TNN ($r = 0.41$), and AUDPC and NEN ($r = 0.42$) (Table 6), suggesting that fungicidal activities, irrespective of combining cultural and host resistance tactics, against *E. pisi* similarly impact the activities of symbiotic nitrogen-fixing bacteria during the growing

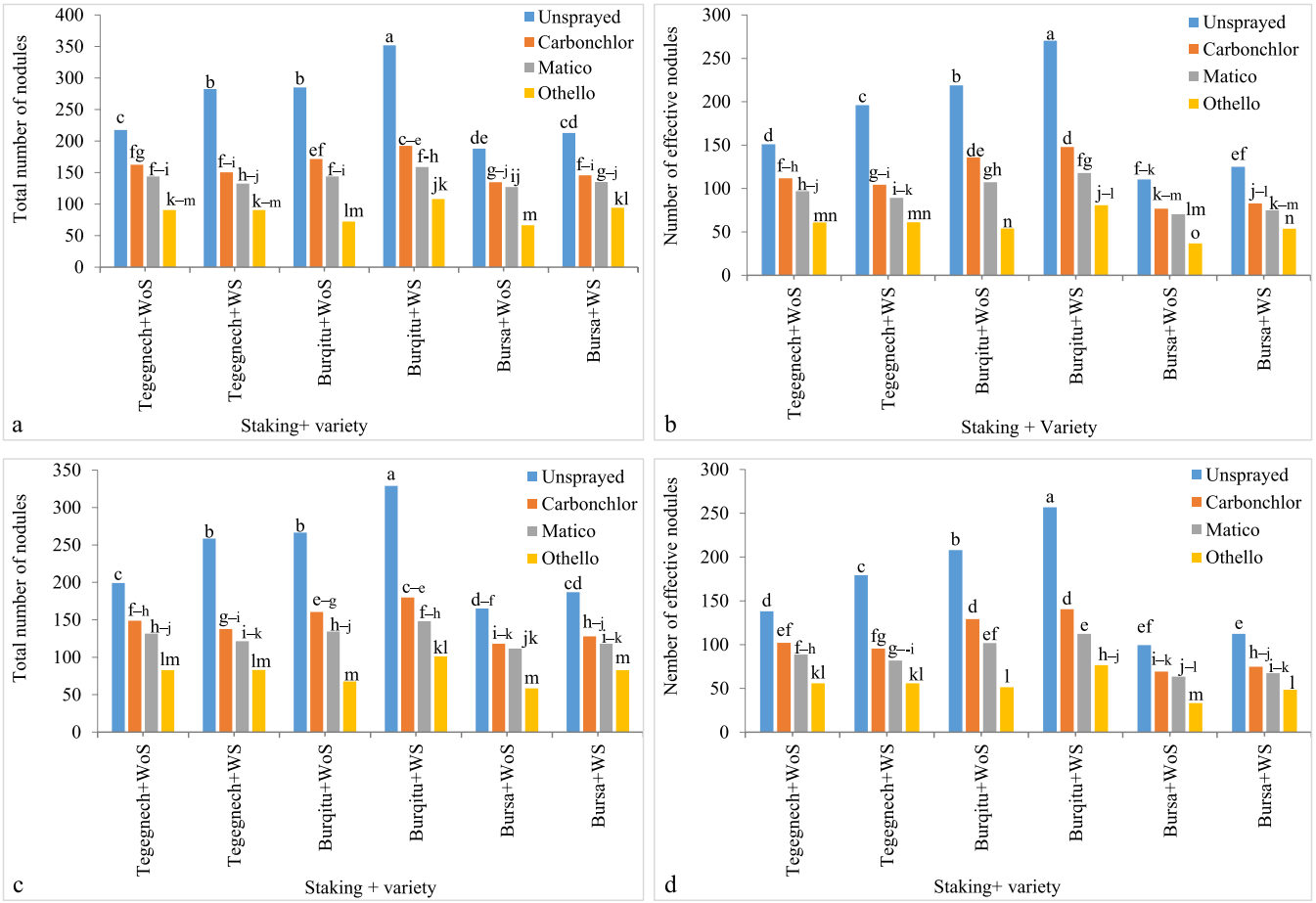


FIGURE 4 | Combined effects of staking, variety, and fungicide application on the total and effective number of nodules in field pea varieties at Bonke (a,b) and Chencha (c,d) in southern Ethiopia during the 2020 and 2021 main cropping seasons. *Note:* WoS = without staking; WS = with staking.

periods. In contrast, AUDPC values exhibited an inverse and highly significant ($p < 0.0001$) association with PH ($r = -0.35$), NPP ($r = -0.41$), NSP ($r = -0.42$), HSW ($r = -0.52$), and GY ($r = -0.50$). Similar associations between other epidemiological and agronomic parameters were also observed at Chencha (Table 6).

Results also showed negative correlations and significant ($p < 0.05$) relationships were found between the NEN and PH ($r = -0.31$), NPP ($r = -0.40$), NSP ($r = -0.33$), HSW ($r = -0.28$), and GY ($r = -0.31$) (Table 6), indicating there was competition for resource growth, development, and physiological activities between plants and symbiotic nitrogen-fixing bacteria during the growing periods. On the other hand, a significant ($p < 0.001$) relationship and a positive correlation ($r = 0.29$ to 0.78) were observed between and among agronomic characters at Chencha over time. Similar trends were noted in the correlations between and among epidemiological components, agronomic traits, and nodule parameters at Bonke over the cropping years (Table 6).

Results obtained from an integral model showed that there were significant ($p < 0.001$) relationships between GY and AUDPC for yield loss contributions at Bonke and Chencha in the 2 years (Figure 5). The estimated yield losses of 37.81% at Bonke and 46.29% at Chencha were due to cumulative disease pressure during the growing periods of field peas. As the level of AUDPC increased, GY exhibited a linear decline toward the horizontal axis, signifying high losses in the tested varieties. That is, for every 1-unit rise in AUDPC value, there was a corresponding yield loss of 0.0028 units at Bonke and 0.0067 units at Chencha over the cropping years. The model indicated that for every unit of PM progression, there were yield losses of 0.0028 t ha^{-1} at Bonke and 0.0067 t ha^{-1} at the Chencha experimental areas over the two cropping seasons (Figure 5).

3.7 | Economic Returns due to Integrated Management of PM

Economic feasibility analyses showed that both NR and BCR varied among the evaluated treatments across locations in the 2 years (Table 7). The highest mean NR ($2538.14 and $2464.23 ha^{-1}) and BCR (6.95 and 5.61) values were obtained from plots of the variety Burqitu with staking and Othello fungicide spray at 10-day intervals for three consecutive sprays at Bonke and Chencha, respectively. The lowest mean NR and BCR values were computed from plots without staking and fungicide spray across all varieties, mainly in the variety Tegegnech (Table 7). At Bonke, combining staking and Othello fungicide

TABLE 5 | Combined effects of staking, variety, and fungicide application on the yield advantage of field pea and the relative yield losses caused by powdery mildew at Bonke and Chencha in southern Ethiopia during the 2020 and 2021 main cropping seasons.

Treatment combination			Relative yield loss, Bonke[a]				Yield[b] increase (%)	Relative yield loss, Chencha[a]				Yield[b] increase (%)
Variety	Cultural practice	Fungicide	NPP loss (%)	NSP loss (%)	HSW loss (%)	Yield loss (%)		NPP loss (%)	NSP loss (%)	HSW loss (%)	Yield loss (%)	
Tegegnech	Without staking	Unsprayed	−48.06	−54.47	−39.50	−73.72	0	−54.26	−46.05	−38.82	−85.35	0
		Carbonchlor	−37.60	−43.33	−30.67	−51.19	85.71	−40.81	−36.95	−34.10	−73.68	79.69
		Matico	−32.66	−35.24	−26.99	−46.76	102.60	−36.75	−32.85	−28.12	−64.30	143.75
		Othello	−18.60	−28.31	−31.46	−37.20	138.96	−18.22	−28.01	−29.45	−59.27	178.13
	With staking	Unsprayed	−36.24	−36.64	−17.63	−58.36	58.44	−43.99	−25.12	−15.02	−63.84	146.88
		Carbonchlor	−23.55	−21.01	−5.16	−28.67	171.43	−27.53	−12.46	−8.38	−42.56	292.19
		Matico	−17.44	−9.64	0	−31.74	159.74	−22.51	−6.72	0	−23.57	421.88
		Othello	0	0	−5.91	0	280.52	0	0	−1.85	0	582.81
Burqitu	Without staking	Unsprayed	−52.13	−57.66	−38.79	−79.25	0	−45.26	−42.92	−36.29	−75.53	0
		Carbonchlor	−41.81	−38.68	−29.20	−65.57	65.91	−33.31	−35.26	−28.52	−71.73	15.53
		Matico	−34.57	−38.42	−30.86	−62.74	79.55	−35.28	−35.42	−31.19	−67.46	33.01
		Othello	−18.35	−28.22	−26.26	−54.95	117.05	−18.80	−28.18	−28.29	−57.72	72.82
	With staking	Unsprayed	−41.65	−41.09	−16.77	−66.98	59.09	−32.65	−20.68	−11.44	−61.28	58.25
		Carbonchlor	−28.72	−14.49	−3.42	−38.44	196.59	−26.05	−24.23	−3.85	−42.99	133.01
		Matico	−20.05	−14.03	−6.01	−23.11	270.45	−20.20	−10.22	−4.12	−23.28	213.59
		Othello	0	0	0	0	381.82	0	0	0	0	308.74
Bursa	Without staking	Unsprayed	−38.86	−54.22	−40.81	−79.55	0	−40.50	−42.21	−51.31	−87.36	0
		Carbonchlor	−48.84	−46.03	−36.49	−66.13	65.63	−34.34	−36.15	−42.45	−73.90	106.52
		Matico	−32.27	−38.45	−34.56	−55.27	118.75	−18.36	−34.70	−36.36	−69.51	141.30
		Othello	−18.70	−28.49	−27.35	−48.24	153.13	−20.84	−28.11	−28.06	−63.19	191.30
	With staking	Unsprayed	−24.61	−36.08	−18.83	−67.73	57.81	−27.11	−19.75	−32.31	−71.15	128.26
		Carbonchlor	−37.40	−24.66	−12.87	−30.03	242.19	−19.44	−11.21	−19.84	−43.68	345.65
		Matico	−16.76	−14.01	−9.86	−19.81	292.19	0	−9.13	−11.46	−23.08	508.70
		Othello	0	0	0	0	389.06	−2.81	0	0	0	691.30

Abbreviations: HSW = hundred seed weight; NPP = number of productive pods per plant; NSP = number of seeds per pod.

[a]Relative yield loss due to PM disease was estimated as the percentage reduction of study parameters with the maximum protected plots compared to the less protected plots for each of the tested pea varieties and fungicides at each location in the cropping years.

[b]Yield increase for each variety over the control was determined as the percentage yield advantage of the difference between the best protected and less protected/control plots at each location in the cropping years.

TABLE 6 | Pearson coefficients of correlation (*r*) between and among epidemiological and agronomic parameters under combinations of staking, variety, and fungicide application at Bonke (upper diagonal) and Chencha (below diagonal) in southern Ethiopia in 2020 and 2021 cropping seasons.

Parameter	PSI7	PSI8	PSI9	AUDPC	PH	NPP	NSP	HSW	GY	TNN	NEN
PSI7	1	0.96****	0.96****	0.97****	−0.23**	−0.21*	−0.29***	−0.13^{ns}	−0.53****	0.36***	0.40****
PSI8	0.98****	1	0.99****	0.96****	−0.16^{ns}	−0.18*	−0.23**	−0.05^{ns}	−0.53****	0.29****	0.33****
PSI9	0.96****	0.98****	1	0.96****	−0.14^{ns}	−0.15^{ns}	−0.21*	−0.04^{ns}	0.53****	0.31***	0.36****
AUDPC	0.97****	0.98***	0.97****	1	−0.21*	−0.23**	−0.28**	−0.11^{ns}	−0.53****	0.28***	0.32****
PH	−0.33****	−0.34****	−0.34****	−0.35****	1	0.53****	0.80****	0.73****	0.49****	−0.18*	−0.23*
NPP	−0.23**	−0.21**	−0.23**	−0.41****	0.43****	1	0.66****	0.45****	0.40****	−0.10^{ns}	−0.51***
NSP	−0.42****	−0.42****	−0.43****	−0.42****	0.78****	0.52****	1	0.75****	0.44****	−0.26***	−0.17*
HSW	−0.53^{ns}	−0.53****	−0.53****	−0.52****	0.54****	0.29**	0.70****	1	0.21*	−0.13^{ns}	−0.29*
GY	−0.50****	−0.49****	−0.52****	−0.50****	0.68****	0.51****	0.78****	0.62****	1	−0.39****	−0.33****
TNN	0.47****	0.44****	0.48****	0.41****	−0.08^{ns}	−0.27**	−0.03^{ns}	−0.13^{ns}	−0.35****	1	0.98****
NEN	0.48****	0.45****	0.49****	0.42****	−0.31*	−0.40****	−0.33*	−0.28*	−0.31*	0.98****	1

Note: PSI7–PSI9 refer to percent severity index at the last three dates of disease assessments at both experimental locations in the cropping years. ns = correlation is not significant ($p > 0.05$).
Abbreviations: AUDPC = area under disease progress curve; GY = grain yield (t ha^{-1}); HSW = hundred seed weight (g); NEN = number of effective nodules; NPP = number of pods per plant; NSP = number of seeds per pod; PH = plant height (cm); TNN = total number of nodules.
****Correlation is significant at $p < 0.0001$.
***Correlation is significant at $p < 0.001$.
**Correlation is significant at $p < 0.01$.
*Correlation is significant at $p < 0.05$.

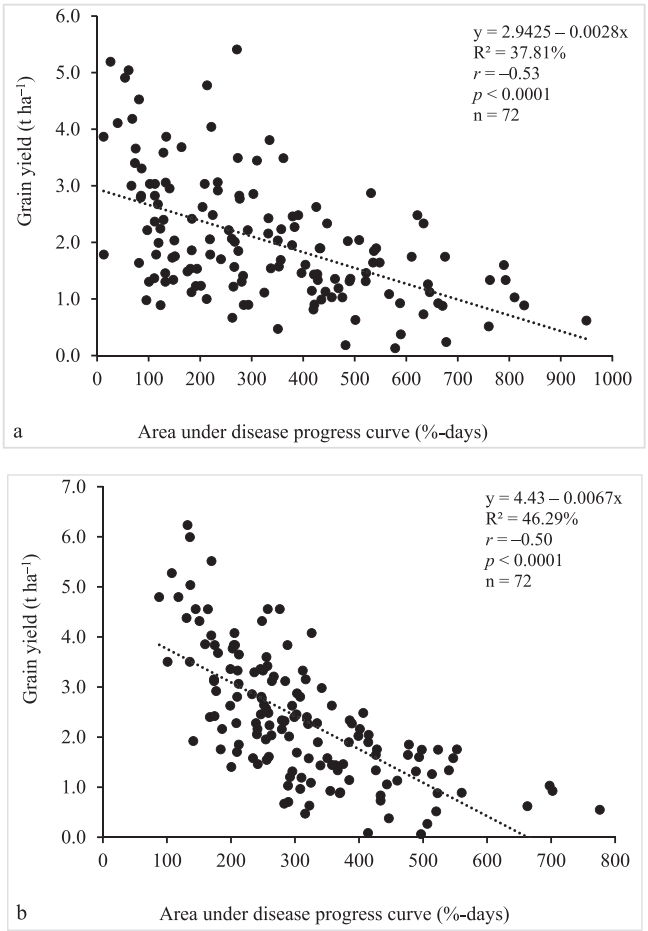


FIGURE 5 | Linear regression of field pea grain yield against area under disease progress curve in plot-wise assessments under a combination of staking, variety, and fungicide spray at Bonke (a) and Chencha (b) in southern Ethiopia across 2020 and 2021 main cropping seasons.

spray with Tegegnech, Burqitu, and Bursa varieties increased NR by 84.42%, 86.93%, and 90.32%; and BCR by 78.89%, 82.30%, and 86.86% over plots left without staking and fungicide spray for each variety, respectively. Closely similar tendencies were computed in the economic feasibility advantages for the same treatment combination over unmanaged control plots for each variety at Chencha (Table 7).

4 | Discussion

Foliar diseases, particularly PM, hinder field pea and legume production worldwide, including in Ethiopia, leading to significant yield losses (Barilli et al. 2019; Sharma et al. 2025). Despite sustainable management efforts, fungicides remain the primary control method (Fondevilla and Rubiales 2012; Suresh et al. 2025). However, continuous pesticide application has resulted in chemical residues in goods, soil, and water (Itoh 2014), as well as the emergence of resistant pathogens, posing risks to ecosystems and nontarget organisms (Mostafalou and Abdollahi 2012). To address these issues, it is essential to adopt integrated measures that minimize pesticide use and promote eco-friendly, cost-effective strategies. Combining cultural, varietal, and chemical tactics can effectively manage plant diseases, decrease disease pressure, enhance yields (Campbell and Madden 1990; Madden et al. 2017), and reduce health risks while maximizing social benefits and sustainability in agricultural practices (Garcia-Figuera et al. 2024).

Findings of the present study revealed that significant variations were observed due to the effects of treatments imposed on the study parameters across locations and years. The spatiotemporal analysis demonstrated that Bonke had relatively higher PM severity and AUDPC than Chencha, regardless of treatments applied, which could be due to the rotation of pea production season after season, the presence of a reservoir of pathogen inocula, and favorable weather variables. Such epidemic factors, along with late sowing in the area, may facilitate host–pathogen interaction, conidial germination, and subsequent disease development. Earlier reports indicated that *E. pisi* is highly adapted and able to survive in a broad range of environmental situations, such as mild to warm temperatures (15°C–25°C) and humidity levels exceeding 70%, which persist for 4 to 5 days (Wspanialy and Moussa 2016), or even under extreme weather conditions (Nag and Khare 2017) for infection and epidemic development. These ranges of meteorological information were also observed at Bonke and Chencha during the study periods (Figure 1) and are reported to be risk factors for *E. pisi* conidial germination and infection under field settings. In addition, late sowing could extend crop growth conditions from heavy rainy days to warm and sunny periods, thereby causing the coincidence of critical growth stages (pod formation and grain filling) of field peas with peak disease periods that promote *E. pisi* infection and epidemic development during late growing periods (Jarvis et al. 2002).

Field observations indicated that the integrated use of staking, variety, and fungicide spray for PM management considerably lowered symptomatic activities and disease progression compared to unmanaged plots. For instance, disease severity and AUDPC values were significantly reduced by fungicide application in all test varieties, with or without staking, during the study periods, implying that fungicide applications interrupt the capacity of the pathogen to germinate, infect, and sporulate during the epidemic periods. Falloon and Viljanen-Rollinson (2001) and Fondevilla and Rubiales (2012) also confirmed that fungicides from various chemical classes and modes of action delayed infection and the epidemic development of PM in field peas. On the other hand, Andualem et al. (2020) and Maria et al. (2024) found significantly variable efficacy of various fungicides against PM in field peas under field conditions, irrespective of the varieties grown and other crop husbandry practices.

Of fungicides, Othello-sprayed plots demonstrated lower PM metrics than Carbonchlor- and Matico-sprayed plots, which could be most likely attributable to the kind and quantity of active substances that made up the fungicide formulations. Mengesha (2020) and Maria et al. (2024) argued that chemical class, active substance type, and associated amounts in fungicides caused significant variation between and among fungicides used for the management of various fungal diseases and agronomic performances of crops, independent of varieties tested, fungicide rate, and spray frequency. A prior report also suggested that host resistance, fungicide effectiveness, foliar coverage, disease status, and ecological conditions are the main determinants of foliar fungicide effectiveness and yield potential

TABLE 7 | Economic feasibility analysis of combined implementation of staking practice, variety, and fungicide spray against powdery mildew of field pea at Bonke and Chencha in southern Ethiopia during the 2020 and 2021 main cropping seasons.

Treatment combination			Bonke experimental areas[a]						Chencha experimental areas[a]					
			Observed GY (t ha^{-1})						Observed GY (t ha^{-1})					
Variety	Cultural practice	Fungicide	2020	2021	Mean	AGY (t ha^{-1})	NR ($ ha^{-1})	BCR	2020	2021	Mean	AGY (t ha^{-1})	NR ($ ha^{-1})	BCR
Tegegnech	Without staking	Unsprayed	0.90	0.63	0.77	0.69	255.64	0.95	0.38	0.89	0.64	0.57	177.26	0.51
		Carbonchlor	1.44	1.42	1.43	1.29	637.73	1.86	0.98	1.32	1.15	1.04	559.35	1.33
		Matico	1.49	1.63	1.56	1.40	721.33	2.11	1.42	1.69	1.56	1.40	642.95	1.53
		Othello	1.88	1.79	1.84	1.65	906.86	2.61	1.58	1.98	1.78	1.60	828.47	1.95
	With staking	Unsprayed	1.40	1.03	1.22	1.09	541.73	1.89	1.03	2.13	1.58	1.42	467.82	1.30
		Carbonchlor	2.09	2.09	2.09	1.88	1068.22	2.96	1.58	3.44	2.51	2.26	994.31	2.29
		Matico	1.99	2.00	2.00	1.80	1007.42	2.79	2.28	4.40	3.34	3.01	933.51	2.15
		Othello	2.93	2.93	2.93	2.64	1641.34	4.50	2.90	5.83	4.37	3.93	1567.43	3.57
Burqitu	Without staking	Unsprayed	0.92	0.84	0.88	0.79	331.64	1.23	0.84	1.22	1.03	0.93	253.26	0.73
		Carbonchlor	1.86	1.05	1.46	1.31	652.93	1.91	0.92	1.45	1.19	1.07	574.55	1.36
		Matico	1.94	1.22	1.58	1.42	736.53	2.15	1.22	1.51	1.37	1.23	658.15	1.56
		Othello	2.05	1.76	1.91	1.71	952.46	2.74	1.62	1.94	1.78	1.60	874.07	2.05
	With staking	Unsprayed	1.43	1.36	1.40	1.26	670.93	2.34	1.36	1.90	1.63	1.47	597.02	1.66
		Carbonchlor	3.29	1.92	2.61	2.34	1417.82	3.93	1.92	2.88	2.40	2.16	1343.91	3.09
		Matico	3.98	2.54	3.26	2.93	1866.22	5.18	2.54	3.92	3.23	2.91	1792.31	4.13
		Othello	4.36	4.12	4.24	3.82	2538.14	6.95	3.38	5.03	4.21	3.78	2464.23	5.61
Bursa	Without staking	Unsprayed	0.82	0.46	0.64	0.58	172.04	0.64	0.37	0.54	0.46	0.41	93.66	0.27
		Carbonchlor	1.35	0.76	1.06	0.95	379.33	1.11	0.71	1.19	0.95	0.86	300.95	0.71
		Matico	1.67	1.13	1.40	1.26	614.93	1.79	0.76	1.45	1.11	0.99	536.55	1.27
		Othello	1.79	1.45	1.62	1.46	762.46	2.20	1.13	1.54	1.34	1.20	684.07	1.61
	With staking	Unsprayed	1.27	0.74	1.01	0.90	397.33	1.39	0.71	1.39	1.05	0.95	323.42	0.90
		Carbonchlor	2.98	1.39	2.19	1.97	1136.62	3.15	1.37	2.72	2.05	1.84	1062.71	2.45
		Matico	2.95	2.07	2.51	2.26	1357.02	3.76	2.07	3.52	2.80	2.52	1283.11	2.95
		Othello	3.61	2.65	3.13	2.82	1778.14	4.87	2.65	4.63	3.64	3.28	1704.23	3.88

Abbreviations: AGY = adjusted grain yield (at 10% down); BCR = benefit–cost ratio; GY = grain yield; NR = net return.

[a]Mean unit prices of field pea 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 49.99 [2021]) at the time of marketing at Bonke and Chencha, respectively.

of a given crop (Gan et al. 2006). In this context, the significant decline in disease metrics in this study may result from the combined suppressive effects of fungicides, staking practices, and the genetic background of crop varieties, all of which are known to reduce infection rates, lesions, inoculum spread, and the occurrence of secondary infective propagules caused by the pathogen in current field settings.

Findings demonstrated that significantly variable PM epidemics were recorded among staking practices, pea varieties, and fungicides. Staking practices do not have direct roles in PM management. Rather, they have indirect effects by supporting the pea vines/tendrils to attach to structures for physiological resistance, providing light interception for efficient photosynthesis, keeping leaves off the ground, facilitating better air circulation through the canopy, and maintaining lower temperatures and humidity around the plants, which are less favorable for disease initiation and subsequent development. According to Hoque et al. (1994), such conditions could prevent PM from spreading and further establishing itself in the fields, which would improve crop health, make harvesting easier, increase yield, and enhance yield quality. Without staking, stands may become susceptible to diseases and be toppled by wind or heavy rain, leading to a decline in yield. Although staking operations significantly reduced PM pressure in all pea varieties, regardless of fungicides applied, relying solely on staking may not be adequate to control the disease. It is commendable to supplement staking with additional disease management tactics, as some staking practices can promote plant vigor and create dense canopies in the field, which can lead to a favorable microclimate for PM development. In this regard, comparable analogies have been reported by Feng et al. (2017).

The evaluated pea varieties had different magnitudes of PM components during the study. For example, plots planted with the variety Bursa, combined with staking and any fungicide spraying, experienced lower disease metrics than the Tegegnech and Burqitu varieties, which received the same treatments. These differential responses to PM disease could be ascribed to varietal genetic background and ecological adaptability. A study by Fondevilla et al. (2007) examined 67 pea lines, including those from Ethiopia, for *E. pisi* resistance; results showed diverse responses affected by genetic differences among pea lines and *E. pisi* biotypes. Fikere et al. (2010) in Ethiopia and Sharma et al. (2025) in India also found variable responses of field pea genotypes to PM disease and agronomic traits under diverse conditions due to their genetic constituents and environmental adaptability. In the current study, the disease was not observed in the variety Bursa until the third severity assessment date in both locations and years, which is attributed to the genetic resistance of this variety to PM disease. On the contrary, the variety Burqitu was initially reported to be moderately resistant; however, the first signs and the highest levels of PM pressure were observed on this variety across locations over the years, suggesting that there might be diverse virulent strains and genetic variability among *E. pisi* pathotypes. This leads to the collapse of formerly efficient resistance genes in this variety in the study areas compared to locations where it was tested and released, as supported by Parthasarathy et al. (2017) and Seethapathy et al. (2022).

However, separate practices of management tactics may have their own limitations regarding disease suppression compared to integrated approaches in the cultivation of a given crop (Madden et al. 2017). In this context, the current study indicated that using an integration of cultural, varietal, and chemical tactics significantly lowered disease pressure, in contrast to the separate implementation of each tactic. More specifically, the disease epidemics were significantly reduced when pea varieties were combined with staking practices and foliar spraying of Othello fungicide, followed by Carbonchlor and Matico, at Bonke and Chencha over the years. Previous reports indicated that combining tolerant varieties and fungicide applications with comprehensive staking practices in Ethiopia (although there is no quantified evidence for its effects on PM control) (MoANR and EATA 2018), along with various varieties, fungicides, botanicals, biologicals, and organic amendments in Nepal (Jamal et al. 2025), significantly lowered disease metrics against PM when compared to the separate application of each tactic in field peas. Otherwise, applications of sole tactics are inadequate to provide a sufficient level of disease reduction due to variability in disease-causing pathogens, genotypic responses across agroecologies, farming modifications, and prevailing weather conditions (Agrios 2005; Madden et al. 2017).

Results of this evaluation also revealed that the integration of staking, variety, and fungicide application significantly improved the performance of agronomic traits in the test varieties across locations and over years. This suggests that using integrated measures could promote crop development while mitigating the negative effects associated with PM. Highly infected plots had the lowest yield and yield-related components, including PH, NPP, NSP, and HSW. Such a phenomenon could be partly elucidated by the formation of lesions on leaves, stems, flower buds, pods, and petioles, resulting in premature leaf senescence, defoliation, and stem collapse in peas. Leaf lesions impede photosynthesis while also hindering respiration by depleting the energy and biomass of the plant. Consequently, these damages lead to diminished plant vigor and yield, which causes significant losses in yield and seed size, as supported by Falloon and Viljanen-Rollinson (2001). Conversely, integrated measures improved plant development, defense systems, and physiological processes, thereby enhancing grain yield, yielding advantages, minimizing yield loss, and reducing disease effects, as confirmed by Semaškienė et al. (2022), who reported that integrated approaches reduced PM and improved agronomic performance in field pea under field conditions.

On the other hand, uncertainties in nodulation and effectiveness were observed among evaluated pea varieties, irrespective of cultural practices and fungicide applications. Such disparities among pea varieties for nodule traits can be explained by the genetic potential of the crop and agronomic practices such as low levels of soil nitrogen in the surroundings, which trigger the plant roots to emit flavonoids that attract rhizobia. In relation to these arguments, Plestenjak et al. (2024) reported variable responses among bean genotypes for nodule performance across diverse environmental setups, which could be due to large variations in bean gene pools, agronomic management levels, and edaphic-climatic conditions. Although integrations of cultural, varietal, and chemical methods reduced PM pressure and improved

agronomic attributes of pea varieties, this approach negatively affected nodule components. This observation is noted by comparing plots with and without fungicides, as fungicide-sprayed plots had lower TNN and NEN than untreated ones. These negative contributions could be associated with the fungicidal effects that reduce the activity of symbiotic nitrogen-fixing agents, as the fungicides did for *E. pisi* activities. The systemic nature of the fungicides also perhaps influences rhizobium bacteria activities, potentially disrupting essential processes necessary for nodule development and function, leading to ineffective or slow formation of nodules.

In this regard, some studies reported that foliar fungicide spray greatly improves the nodulation process by lowering disease pressure in legumes (El-Kholy et al. 2021; Terefe et al. 2024; Mengesha et al. 2025), while other studies dispute the current findings and claim that it has no effect on nodulation (Cardillo et al. 2019). Nevertheless, earlier reports indicated that types of rhizobia strains and fungicide administration methods could influence nodulation (Ramos and Ribeiro 1993). Related to the present results, Gorshkov et al. (2020, 2023) reported that foliar fungicide applications, having different active substances and concentrations, on field pea genotypes significantly reduced nodule numbers by disturbing the physiological activities of nitrogen-fixing rhizobium bacteria and the reactions between the roots of the pea plants and the agents over controls. The situation suggests that the timing and methods of fungicide application, the amount and active ingredients in the product, the growth stages of plants, and edaphic-climatic conditions might determine nodule formation and development under field conditions; related analogies have been reported by Hossain et al. (2017).

In this study, losses caused by PM on NPP, NSP, HSW, and GY varied among treatments. This might be due to varietal genetic background, disease status, efficiency of measures taken, and other factors. In other parts of the world, reported losses in grain yield, pod number, and pod weight have ranged from 50% to 100%, 21% to 31%, and 26% to 47%, respectively, depending on varietal susceptibility, levels of field management, and environmental conditions (Suresh et al. 2025). Yield loss in field pea is linked to intense PM pressure, likely stemming from favorable weather conditions, the nature of the pathogen infecting all aboveground plant parts, a reduction in the photosynthesizing leaf area, and diminished photosynthetic efficiency; such conditions cause leaf defoliation and stem breakage, culminating in significant yield reductions (Ayres 1977; Jarvis et al. 2002). Guant (1995) also acknowledged that the effects of plant diseases contribute significantly to yield reductions in cultivated crops at all stages of disease development. Moderate levels of other disease intensity and factors could also be considered responsible for yield losses besides PM disease; the current study did not fully elucidate their effects. However, it is conceivable to understand that practicing an integration of proper staking practices, varieties, and fungicide spray ameliorates agronomic attributes while also lowering PM pressure, damage caused by PM disease on peas, and yield losses, thereby enhancing pea advantages such as production and productivity. Prior studies have also corroborated that integrated measures can enhance the agronomic attributes of legume crops while reducing disease pressure under various environmental conditions (Mengesha, Terefe, and Cheleko 2022; Bitew et al. 2022; Jamal et al. 2025).

Correlation matrices showed that there were diverse associations among and between disease, agronomic, and nodule parameters. It was observed that there were highly significant and positive associations between disease metrics, indicating that these metrics were related to one another. Such situations suggest the disease built up at a faster rate on unmanaged plots than on pea varieties treated with fungicide sprays, whether staked or not. Previous scholars also argued that there is a positive and significant link among epidemiological indicators and progressive epidemic development during disease outbreak periods. For instance, Maria et al. (2024) reported that PM disease parameters were highly significant and strongly linked with one another. Campbell and Madden (1990) and Guant (1995) also suggested that a significant correlation exists among epidemiological indicators during disease outbreak periods. Similarly, disease metrics and nodule counts established highly significant and positive correlations among themselves. This suggests that applied fungicides, regardless of pea plant varieties and staking methods, significantly affected the activities of nitrogen-fixing agents, parallel to the effects on *E. pisi*. This impact reduces the symbiotic association between the roots of the pea plant and the rhizobium bacteria necessary for nitrogen fixation. Previous studies contrast with the current findings, indicating that foliar fungicide spray is not associated with nodulation (Cardillo et al. 2019), while others suggest it is highly associated with the nodulation process by reducing disease pressure in legumes (Terefe et al. 2024; Mengesha et al. 2025). Supporting the current findings, Gorshkov et al. (2020) found a negative association among parameters on fungicide-sprayed and untreated units, which is credited to the deterioration of rhizobium bacteria's symbiosomes and, as a result, minimized the symbiotic relationships between nitrogen-fixing agents and the roots of pea plants.

Likewise, agronomic parameters established positive and strong associations among themselves since the ultimate goal of potential yield is not a single trait contribution but a combination of several agronomic components, along with proper field management, genotype genetic potential, environmental adaptability, and tolerance to biotic stresses. Other research reports also indicated that agronomic parameters had positive and highly significant associations with one another in the correlation matrix studies of legume crops (Singh and Singh 2005; Teferi et al. 2018; Yimam et al. 2024). Conversely, the correlation analyses in the present study identified that disease scores and nodule parameters had negative and highly significant correlations with agronomic traits, which attested to the economic significance of PM in causing stress to the crop and resource competition among agronomic traits and nitrogen-fixing bacteria for growth and development. This inverse relationship between disease components and agronomic traits could suggest that disease metrics are key elements in predicting yield losses.

Regarding this, Teshome and Tegegn (2017) and Maria et al. (2024) found a strong negative association between disease metrics and agronomic traits, which are explained by the worsening of physiological activities of the host by causal pathogens, subsequently weakening the host's growth and

development and eventually reducing crop agronomic performance (Guant 1995; Jarvis et al. 2002). Similarly, certain nodule characters may inversely associate with agronomic trait potential since a large nodule count can raise carbon expenditures for the plant, potentially changing the legume-rhizobium interface from a mutualistic symbiosis to a parasitic relationship due to resource competition, thereby adversely affecting total crop performance. In this regard, previous reports indicated that there were variable relationships (both positive and negative correlations) among nodule and agronomic characters (Shrestha et al. 2021; Dhillon et al. 2022; Plestenjak et al. 2024; Sajjad et al. 2024). These scholars suggested that a positive correlation, evidenced by efficient nitrogen fixation through root nodules, directly enhances crop growth and development by providing a readily available nitrogen source, thereby improving overall crop performance. Conversely, negative relationships indicated that there was resource competition for growth and development, which resulted in a decline in the agronomic performance of the crop.

Furthermore, economic evaluations of integrating cultural, host resistance, and chemical tactics to manage PM and enhance pea productivity exhibited substantial variations among treatment combinations. The highest mean NR and BCR were attained from integrations of the variety Burqitu with staking and Othello fungicide spraying, followed by combinations of the same variety with staking and Matico fungicide application over other treatments across locations and years. This treatment combination established the most cost-effective approach compared to other treatments, and it could be recommended for pea growers to control PM, enhance yield gain, and obtain high economic returns. Of course, the findings of Mengesha, Abebe, et al. (2022), Bitew et al. (2022), Terefe et al. (2024), and Arato et al. (2026) have recognized the viability of integrating chemicals with other management tactics in various pathosystems and suggested that differences in the effectiveness of disease control measures could be due to differences in disease status, varietal genetic backgrounds, environmental adaptability of crop varieties, product quality of chemicals used, and the time and cost associated with production and marketing during the growing seasons.

5 | Conclusions

The study highlights the effectiveness of integrated approaches in managing PM and enhancing agronomic performance in field pea production. Unmanaged control plots experienced high disease pressure and significant yield losses, while fungicide-unsprayed plots showed improved nodulation. The integration of pea varieties with staking and Othello foliar spray notably reduced PM development across locations over time. Remarkable variation in quantitative growth, yield, and yield attributes such as PH, NPP, NSP, HSW, and grain yield was also observed due to combined operations of pea varieties with staking and Othello across locations and seasons. However, fungicide-treated plots had lower nodule counts compared to untreated ones, indicating a negative impact on nitrogen-fixing agents. Economic evaluations revealed that using the Burqitu variety along with staking and Othello spray yielded better monetary benefits than other treatments. Overall, integrated measures present a valuable strategy for managing PM and boosting yield attributes in field pea systems, particularly by combining Burqitu with staking and Othello foliar spray for superior disease management, yield improvement, reduced yield losses, and enhanced economic returns. Thus, it is advisable for farmers in the study areas and elsewhere in analogous agroecologies to manage PM through integrated measures and optimize yield and the highest economic returns. The output of this research contributes to the design of policies for decision-making at the national and international levels for the development and adoption of pea disease and crop management practices, as well as the provision of technical advisory services to pea producers regarding the precise forecast of disease epidemics driven by the interaction of susceptible hosts, virulent pathogens, and favorable environments and their management, considering changing environmental conditions across different cropping systems. Further study is necessary in other agroecologies to determine the resilience of the identified measures in response to ever-changing environmental conditions and to develop concrete recommendations for PM management options via combining cultural, host resistance, and chemical tactics. Moreover, limitations involve focusing on two highland areas in southern Ethiopia for 2 years, restricting broader applicability under diversified agroecologies. Additionally, the limited variety and fungicide programs affect generalization and give concrete recommendations across agroecologies for PM management options and enhanced sustainable pea production. This suggests the need for further field investigations using fungicide-variety combinations across multiple locations over several years.

Author Contributions

Getachew G. Mengesha: conceptualization, investigation, writing – original draft, methodology, validation, writing – review and editing, software, formal analysis, project administration, data curation, supervision, resources, funding acquisition. **Habtamu Terefe:** conceptualization, writing – original draft, methodology, validation, visualization, writing – review and editing, software, formal analysis. **Asnake A. Arato:** investigation, methodology, writing – original draft, writing – review and editing, data curation. **Tariku Simion:** investigation, supervision, resources, writing – original draft, writing – review and editing, funding acquisition. **Dizgo Chencha:** investigation, methodology, writing – review and editing, data curation. **Tuma A. Yadda:** funding acquisition, writing – review and editing, resources, supervision, validation. **Abu Jambo:** writing – original draft, writing – review and editing, visualization, formal analysis. **Meseret T. Suure:** investigation, resources, writing – original draft, writing – review and editing.

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Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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