

Research

Management of faba bean gall (*Physoderma viciae*) through integration of host resistance with fungicides in Meket district, North Eastern Ethiopia

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Abstract

Faba bean (*Vicia faba*) is among the most important crops grown in the highlands of Wollo, Ethiopia. Its yield is generally very low as a result of faba bean gall. Since the disease is new, information is lacking on management options. Therefore, the experiment was carried out to investigate management options using cultivars and fungicides under natural infestation conditions on farmer's field during the 2021 main cropping season in Meket district. Randomized complete block design with 3 replications of Ethylene Bisdithiocarbamate, Triadimefon, Metalaxyl + Mancozeb, and untreated check were combined with varieties of, Walki, Degaga, and local. Statistical Analysis like ANOVA and LSD were determined using SAS 9.2 (2), and the highest grain yield (2.59 t ha⁻¹) was recorded on the Walki variety treated with Triadimefon whereas, the lowest grain yield (1.44 t ha⁻¹) was recorded with the control treatment. The highest and lowest AUDPC of 2080.20% day-1 and 1303.63% day-1 were recorded on the control and Triadimefon treated Walki variety respectively. The novelty of Triadimefon is its ability to both address the primary pathogen and enhance the plant's natural defenses, resulting in improved management of faba bean gall. On the other hand, the Walki variety employs a comprehensive defense approach (structural, genetic, and biochemical) that reduces gall formation and supports a higher yield. Therefore, a combination of Walki and Triadimefon may be suggested as a viable solution for the area in question.

Keywords AUDPC · Faba bean gall · Fungicide · Host resistance · Management

1 Introduction

The faba bean (*Vicia faba* L.) is believed to have originated in the Middle East during prehistoric times [27]. Today, it is widely cultivated in various regions, including Europe, Africa, Central Asia, China, South America, the United States, Canada, and Australia. It is thought that the crop reached Ethiopia from the Middle East via Egypt around 5000 B.C. Ethiopia is now recognized as a secondary diversification hub for the faba bean [36].

Faba beans are enriched in calorie and protein content, with levels ranging from 24 to 30%. The young, green beans can be cooked and eaten as vegetables, while the stalks are often used as firewood for cooking. In crop rotation practices, faba beans are commonly used [17, 42]. In Ethiopia, there is a frequent occurrence of diseases affecting faba beans, particularly epidemics caused by Faba Bean Gall (*Physoderma* sp.) [4]. The use of faba beans as a "break" crop can enhance cereal productivity by reducing the incidence of diseases and cereal cyst nematodes that negatively impact cereals [3].

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Faba bean ranks sixth among legumes in terms of global production. China is the leading producer, followed by Ethiopia [10]. The crop occupies nearly 3.2 million hectares of land worldwide [36], with 0.55 million hectares in Africa [10], and 504,569 hectares in Ethiopia [13]. Despite being the second-largest producer in the world, Ethiopia's share of global production is only 19% [22].

The Ethiopian highlands, situated at an altitude of 1800 to 3000 m above sea level, are the primary region for cultivating faba beans, locally known as "Bakela" [2]. Among legumes, this crop occupies the largest area of land. In the main cropping season of 2020, Ethiopia produced approximately 10,706,365 tons of faba beans [13]. The cultivation of this crop relies entirely on rainfall, predominantly occurring on nitosol and cambisol soils. In the North Wollo Administrative Zone, agricultural activities take place over roughly 11,827.04 acres [13].

The primary limitations on faba bean production arise from a variety of biotic, human, and abiotic factors. Among these, diseases are the most significant biotic threats affecting faba bean yields in Ethiopia. Notable diseases include chocolate spot (*Botrytis fabae*), faba bean rust (*Uromyces viciae-fabae*), black rot (*Fusarium* sp.), Ascochyta blight (*Ascochyta fabae*), faba bean necrotic yellow virus [14, 30], and faba bean gall (*Physoderma viciae*) [15, 18, 41]. Recently, faba bean gall has emerged as a particularly serious concern in the faba bean-producing districts of Ethiopia's Amhara region [8, 12, 18], causing yield losses ranging from 30 to 100% [1].

Due to traditional farming practices such as the absence of fertilizer application, the cultivation of local varieties, and broadcast sowing, the spread of disease is escalating rapidly each year in the Wollo Administrative Zones of the Amhara region. Consequently, farmers have become discouraged from growing the affected crop because of the severe impact of this disease [32]. The initiation of this study was prompted by the reliance on a single management system and a lack of knowledge regarding faba bean gall management [26]. Therefore, it is crucial to develop a sustainable and comprehensive disease management strategy. This study was designed to address these gaps by exploring the management of faba bean gall through the use of integrated varieties and fungicides in the study area.

2 Materials and methods

2.1 Description of the study area for the field experiment

A field experiment was conducted to evaluate the effects of various fungicides and faba bean varieties on the incidence and severity of faba bean gall disease, as well as on yield and yield-related parameters, in farmers' fields located in the Meket district of the North Wollo Administrative Zone, Ethiopia, during the main cropping season of 2021. The specific experimental site was situated in the 029 "Kebele" or Farmers Association, which is considered a hotspot for faba bean gall disease and represents the region's faba bean production [9]. The geographical coordinates of the site are 13° 38' 0.52" N latitude and 47° 14' 0.00" E longitude, with an altitude of approximately 2814 m above sea level. The soil in the area is classified as red-brown clay. The main crops cultivated in this Zone include small cereals, such as wheat and barley, as well as legumes like faba beans and lentils [9] (Fig. 1).

2.2 Experimental materials

Three different fungicides were evaluated in this study: Ethylene Bisdithiocarbamate, Triadimefon, and a combination of Metalaxyl and Mancozeb. Along with an untreated control, three faba bean varieties were used, each with different levels of resistance to faba bean gall disease: Walki (resistant), Degaga (moderately resistant), and a local variety (susceptible) [20, 26].

The Walki variety, released in 2008, is known for its high yield, resistance to waterlogging and black root rot, and wide adaptability. It can be grown at altitudes ranging from 1900 to 2800 m above sea level, providing a yield of 24–52 quintals per hectare. The Degaga variety, released in 2002, is also high-yielding and adaptable, growing well at altitudes between 1800 and 3000 m above sea level, with an average yield of 116 quintals per hectare [40].

The fungicides used were as follows: Mancozeb 80 WP (Ethylene Bisdithiocarbamate) is a contact fungicide applied as a foliar spray at a dose of 1.5 kg per hectare; Bayleton 25 WP (Triadimefon) is a systemic fungicide applied as a seed treatment at a dose of 300 g per 100 kg of seed; and Ridomil Gold MZ 68 WG (Metalaxyl + Mancozeb) is also a systemic fungicide, applied as a foliar spray at a dose of 2.5 kg per hectare [5, 9].

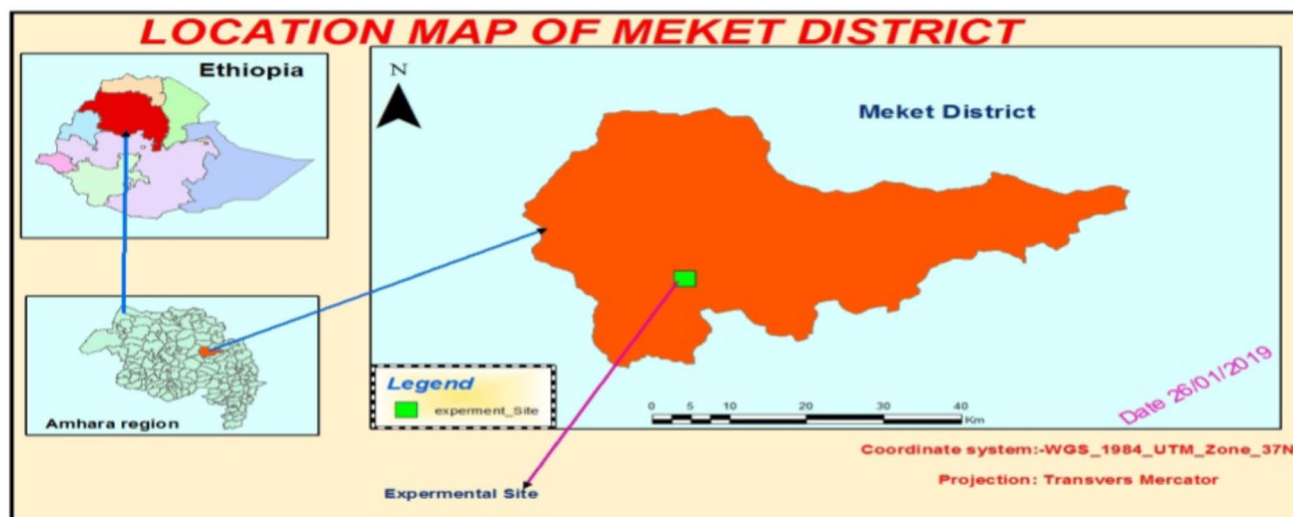


Fig. 1 Location map of the experimental site during 2021 main cropping season

2.3 Treatments, experimental design, and procedures

The experiment was conducted using a randomized complete block design (RCBD) in a factorial arrangement with three replications. Each plot measured 2 m × 1.6 m and contained 20 plants arranged in four rows, with an intra-row spacing of 10 cm and an inter-row spacing of 40 cm. To separate plots and replications, gangways of 0.5 m and 1 m were employed, respectively. A total of 12 treatment combinations were evaluated for the management of faba bean gall disease.

Before sowing, the seeds were dressed with Triadimefon at the time of planting [9]. The fungicides Ethylene Bisdithiocarbamate and Metalaxyl + Mancozeb were applied to the leaves three times, with a 10-day interval between applications [5]. For the plots that did not receive fungicide treatment, only water was sprayed to maintain uniform moisture levels. Knapsack sprayers, calibrated to deliver 300 L of water per hectare, were used for the spraying. Plastic sheets were employed to protect the plants from fungicide drift during applications [5].

At planting, a full dose of fertilizer in the form of NPS was applied, consisting of 38 kg ha⁻¹ of phosphorus, 19 kg ha⁻¹ of nitrogen, and 7 kg ha⁻¹ of sulfur. This was applied immediately below the seed, and covered with a thin layer of soil to prevent direct contact with the seed [5]. Throughout the duration of the trial, all other non-experimental variables and agronomic practices were implemented uniformly across the entire experimental area [5].

The methods followed the relevant guidelines and regulations set forth by the Ethiopian Ministry of Agriculture and adhered to various research recommendations based in Ethiopia.

2.4 Disease assessment

In a net plot measuring 1.44 m², the disease severity was assessed using 10 pre-tagged plants. For each plant in the plot, the prevalence of the disease was recorded. Since the initial manifestation of the disease, evaluations of its condition were conducted every 10 days.

2.5 Data collection from field experiments

2.5.1 Disease parameters

The number of days until disease onset was recorded as 44 days after sowing. Disease incidence was calculated as the percentage of plants showing disease symptoms out of the total number of plants evaluated at ten-day intervals, starting from the onset of the disease [23]. Disease severity was assessed using the 0–9 disease scoring scale shown in Table 1, which estimates the proportion of the leaf and stem area affected by the disease [16].

The percentage severity index (PSI) was derived from the severity grades used for analysis [38]. The percent relative grain yield loss (RYL%) represents the reduction in parameters [31], while the yield increases over control (YIOC%) are also calculated based on the same source [31]. The Area Under Disease Progress Curve (AUDPC) serves as a measure of the progression of a plant disease epidemic [11]. It takes into account the initial disease intensity, the rate of progression, and the duration of the epidemic to predict the final disease intensity [25]. Using the formula from reference [34], the AUDPC was calculated for each plot and reported in % day.

The disease progress rate allows for yield predictions based on the level of disease pressure, while the Area Under the Disease Progress Curve (AUDPC) measures the speed at which the disease develops in one treatment compared to another [24]. The Logistic model, represented as $\ln[Y/(1-Y)]$ [37], and the Gompertz model, represented as $-\ln[-\ln(Y)]$ [6], were compared for estimating disease progression parameters for each treatment. The transformed data were regressed over time (Days After Planting, DAP) to identify the best-fitting model. The goodness of fit for each model was evaluated based on the coefficient of determination (R^2) and the standard error of residuals (SE). The most suitable model was then employed to determine the apparent rate (r) of disease progression. This disease infection rate was subsequently used in the analysis of variance (ANOVA) to compare disease progression among the different treatments.

2.5.2 Crop parameters

Days to 50% emergence was recorded as the number of days from planting until 50% of the plants in each plot had germinated. Days to 50% flowering was calculated as the number of days from germination until half of the plants in the row produced their first blooms. Days to 90% maturity were determined by counting the days until 90% of the leaf surfaces turned yellow, indicating signs of senescence.

To measure plant height (cm), the height from the ground to the tips was recorded for five fully grown plants from the net plot area. For the number of pods per plant, the average number of pods was recorded from five randomly chosen plants out of ten pre-tagged ones. The number of seeds per pod was assessed by harvesting five randomly selected plants per plot to determine the average number of seeds per pod.

The hundred seed weight (g) was recorded at a moisture level of 10.5% by weighing 100 seeds randomly selected from each plot's yield. Straw yield (t/ha) was measured by recording the straw yield per plot and converting it to tons per hectare. The grain yield per plot (g) was measured from the net plot area at a moisture level of 10.5%. Finally, the total grain yield (t/ha) was calculated by converting the grain yield from grams per plot to tons per hectare.

2.6 Data analysis

To assess the treatment effect, the collected data was analyzed using analysis of variance (ANOVA) with SAS software version 9.2, following the methodology outlined in references [21] and [33]. Based on the results of the ANOVA, the least significant difference (LSD) values were used to identify variations between treatment means at a 5% significance level, as indicated in reference [21]. Additionally, data on disease intensity, grain yield, and yield components were correlated using Pearson's method to evaluate the strength of the relationship among these variables, based on the correlation coefficient (r) value. A linear regression model was employed to predict yield based on the severity of faba bean gall.

Table 1 Ding disease severity scoring scale of faba bean *Ascochyta* blight

Index	% of infected plant tissue	Nature of infection
0	0	No disease symptom observed
1	< 2%	A few, very small (< 2 mm ²) lesion on the leaves
2	2–5%	Very small (< 2 mm ²) lesion
3	6–10%	Many small lesions (< 2–5 mm ²)
4	11–25%	Many small lesions, a very few large (> 5 mm ²)
5	26–50%	Many large lesions
6	51–75%	Lesions coalescing
7	76–90%	Lesions coalescing
8	91–99%	Plants darken, stem breakage
9	100%	Plants totally dead

2.7 Economic analysis

The viability of any new technologies in the agriculture industry was evaluated using partial budgeting [12]. This assessment was based on the cost of variable inputs during the 2018 growing season and an estimate of net benefits calculated using the average local market price at the time when most farmers sold their outputs [5]. The cost of faba bean seeds was obtained from the local market, and total sales for one hectare were calculated. We also estimated the cost of each fungicide per kilogram and the overall cost associated with applying it to one hectare of faba bean fields.

Labor costs for applying fungicides were assessed, and we determined the per hectare costs for spraying and equipment. It was assumed that water would be completely free of charge. A partial budget analysis was then conducted to develop a cost–benefit analysis. The marginal rate of return (MRR) was calculated as the ratio of the change in net income to the change in input costs. For the cost–benefit analysis, we assumed that local prices for grain yield per ton and straw were consistent across each treatment.

Costs for labor and spraying equipment were determined based on market rates. The calculations for costs, returns, and benefits were performed on a per-hectare basis, with the expectation that local farmers would receive 90% of the experimental produce. A sensitivity analysis was conducted to identify key factors affecting profitability, address uncertainties, and provide a comprehensive economic assessment that could inform better decision-making in crop management practices. This analysis also took into account price fluctuations, long-term sustainability, and adoption rates by farmers [5].

3 Results and discussion

3.1 Disease onset, level of incidence, and percentage severity index (PSI) of 'faba bean gall

In all the treatments used in this trial, disease symptoms began to appear 44 days after sowing (DAS). The analysis of variance (ANOVA) indicated that the main effects of the varieties and the fungicides showed significant differences ($p < 0.05$) in both disease incidence and percentage severity index during the final assessment date (94 DAS). At this assessment, the local variety exhibited the highest disease incidence at 92%, while the Walki variety had the lowest incidence at 45.21%. Similarly, the local variety also recorded the highest disease severity index at 31.56%, while the Walki variety had the lowest severity index at 22.88% (Table 2). These differences may be attributed to variations in innate genetic resistance among the varieties. This finding aligns with results from the Debre Birhan Agricultural Research Center (DBARC 2015; cited by [39]), which reported differences in faba bean gall incidence among various faba bean genotypes.

In terms of fungicides, the control plots at 94 DAS exhibited the highest disease incidence rate at 49.59%. In contrast, plots treated with Triadimefon showed the lowest disease incidence rate at 43.80% (Table 2). This difference may result from the varying effectiveness levels of the different fungicides. The current findings are consistent with those of [9] and [35], who noted significant variations in faba bean gall incidence among the fungicides used, with Triadimefon-treated plots showing the lowest incidence. However, the results of this study do not agree with those of [39], who reported that fungicide application did not result in significant variation in the percent severity index during the initial disease assessment.

3.1.1 Area under disease progress curve (AUDPC) and Disease progress rate (DPR)

The analysis of variance revealed a highly significant difference ($p < 0.01$) between different varieties and fungicides concerning the area under the disease progress curve (AUDPC) and the disease progress rate. The highest AUDPC value, recorded at 1847.77%-days, was associated with the local variety, followed by the Degaga variety at 1596.78%-days. The lowest AUDPC value was observed in the Walki variety at 1303.63%-days.

To determine the best-fitting model for describing the rate of disease progression, both the Logistic and Gompertz models were tested. The Gompertz model exhibited a higher coefficient of determination (R^2) and smaller residuals (SE) compared to the Logistic model for all assessment dates, leading to the selection of the Gompertz model. The local variety showcased the highest disease progress rate at 0.0347 gompit per day, while the Walki variety demonstrated the lowest rate at 0.0331 gompit per day (see Table 2). This indicates that the disease progress rate of the local variety was 1.04 times faster than that of the Walki variety. Consequently, using the Walki variety reduced the rate of faba bean

Table 2 Main effects of faba bean varieties and fungicides on faba bean gall intensity and crop phenology

Treatment	DI (%) 94 DAS	PSI (%) 94 DAS	AUDPC (%·days)	DPR (gompit day ⁻¹)	ED (days)	FLD (days)	MD (days)
Variety							
Local	49.92 ^a	31.56 ^a	1847.77 ^a	0.0347 ^a	10.42	48.67 ^b	123.67 ^b
Walki	45.21 ^b	22.88 ^c	1410.89 ^c	0.0332 ^c	10.25	53.08 ^a	140.92 ^a
Degaga	46.47 ^b	26.36 ^b	1596.78 ^b	0.0344 ^b	10.42	51.50 ^{ab}	132.67 ^a
LSD ($p \leq 0.05$)	2.61	1.36	98.227	0.0006	-	2.90	8.28
Significance level	*	**	**	**	Ns	*	*
Fungicide							
Metalaxyl + Mancozeb	46.46 ^c	26.58 ^b	1560.68 ^b	0.0337 ^{bc}	10.22	52.11	132.67
Triadimefon	43.80 ^c	24.75 ^c	1446.23 ^c	0.0333 ^c	10.89	52.33	136.67
Ethylene Bisdithiocarbamate	48.97 ^{ab}	27.39 ^b	1670.13 ^b	0.0344 ^{ab}	10.44	50.67	131.11
Control	49.59 ^a	29.01 ^a	1796.88 ^a	0.03492 ^a	9.89	49.22	129.22
LSD ($p \leq 0.05$)	3.01	1.57	113.42	0.0007	-	-	-
Significance level	*	**	**	**	Ns	Ns	Ns
CV (%)	6.53	5.96	7.168	2.205	11.59	6.71	7.39
SE $\pm$	0.98	0.73	41.293	0.0002	0.17	0.52	1.92

LSD least significant difference, DAS Days after sowing, CV Coefficient of variation, SE standard error, ED emergence date, FLD flowering date, MD maturity date, ns non-significant

*significant difference $p \leq 0.05$, ** highly significant difference $p \leq 0.01$ Means with the same letter(s) within a column are not significantly different each other

gall disease progression to 0.0015 gompit per day. This variation in disease resistance may be attributed to the inherent genetic differences among the varieties. These findings are consistent with the reports by authors [20, 28], who noted that the overall disease development was significantly influenced by the varieties used. Similar results were also noted by [29], who found distinct differences among faba bean varieties in disease progression.

The highest value for the area under the disease progress curve (AUDPC) was recorded in the control treatment, with a value of 1796.88%-days. This was followed by Ethylene Bisdithiocarbamate at 1670.13%-days. In contrast, the lowest AUDPC, measured at 1446.23%-days, was observed in the treatment with Triadimefon (see Table 2). The significant differences in AUDPC values among the fungicide treatments indicate that the impact of these fungicides on the growth of faba bean gall disease varied considerably.

These findings align with those of [9, 35], which highlighted that the type of fungicide used substantially affects overall disease progression. The highest disease progress rate was recorded in the control treatment at 0.0349 gompit per day, while the lowest rate, 0.0333 gompit per day, was observed with Triadimefon (see Table 2). This indicates that the disease progression rate in the control group was 1.05 times faster than that with Triadimefon. The use of Triadimefon reduced the rate of faba bean gall disease progression to 0.0016 gompit per day.

These results are consistent with findings from [26], which reported that fungicide treatments were more effective in reducing disease progression rates compared to untreated plots. Furthermore, they noted that lower disease progression rates were observed in plots treated with various fungicides compared to those in untreated control plots.

3.2 Crop phenological parameters

3.2.1 Days to 50% seedling emergence, days to 50% flowering, and days to 90% maturity

The results of the ANOVA revealed that neither the varieties nor the fungicides significantly influenced the days to 50% seedling emergence of faba bean ($p > 0.05$). However, the main factor of varieties showed significant variation ($p < 0.05$) in the days to 50% flowering and the days to 90% maturity. In contrast, fungicides as a main factor and the interaction effects between the two factors did not demonstrate significant differences ($p > 0.05$).

The local variety resulted in the shortest period, taking 48.67 days to reach 50% flowering and 123.67 days to reach 90% maturity. In comparison, the Walki variety exhibited the longest duration, requiring 53.08 days to flower and 140.92 days to achieve 90% maturity (see Table 2). These variations may be attributed to the higher disease pressure observed in

the control plots and the genetic differences among the varieties. This finding aligns with the results reported by [39], which indicated that the local variety had significantly shorter times to 90% maturity compared to improved varieties.

The interaction effects of different varieties with fungicides showed significant variation ($p < 0.05$) in reducing disease incidence, plant height, hundred seed weight, straw yield, and grain yield. There was also a highly significant variation ($p < 0.01$) observed for the percent severity index (PSI) at 94 DAS. However, the interaction effects of the two factors did not show significant variation in the number of pods per plant and the number of seeds per pod ($p > 0.05$).

The highest disease incidence (52.77%) was recorded for the local variety without fungicide treatment, while the lowest incidence (43.40%) was observed with the Degaga variety treated with Triadimefon and Metalaxyl + Mancozeb, which represented a reduction of 9.37% compared to the local variety without treatment. The highest PSI of 35.829% was noted for the local variety with no fungicide, whereas the lowest PSI was seen in the Walki variety treated with Triadimefon (22.713%).

In terms of plant height, the tallest plants (126.27 cm) were recorded for the Walki variety treated with Triadimefon, followed closely by the Degaga variety with Triadimefon (123.20 cm). In contrast, the shortest plant height (90.80 cm) was recorded for the local variety that received no fungicide treatment.

The highest hundred seed weight (HSW) of 62.23 g was observed for the Walki variety treated with Bayleton, while the lowest HSW (38.37 g) was noted for the untreated local variety. The highest straw yield (SY) of 9.26 t ha⁻¹ and grain yield (GY) of 2.59 t ha⁻¹ were also recorded for the Walki variety treated with Triadimefon. Conversely, the local variety without fungicide treatment had the lowest straw yield (5.24 t ha⁻¹) and grain yield (1.44 t ha⁻¹).

The greatest relative yield loss (44.40%) occurred in the untreated local variety, whereas the lowest relative yield loss (22.01%) was recorded for the Walki variety treated with Triadimefon, followed by the Degaga variety with the same treatment. This indicates that using the Walki variety treated with Triadimefon resulted in an additional yield of 0.4440 t ha⁻¹ compared to the control treatment (see Table 3).

This study highlights the differences in intrinsic genetic resistance levels among various faba bean genotypes and the effectiveness of fungicides in managing faba bean gall disease (Figs. 2, 3 and 4). The results align with the findings of previous research [5, 19, 20], which indicated that the incidence and severity of faba bean gall vary based on the combined effects of genotypes and fungicides. Furthermore, it was shown that recommended applications of Triadimefon [9, 35] and Metalaxyl + Mancozeb [5, 35] effectively reduce the occurrence of faba bean gall. Additionally, [39] observed that faba bean gall disease significantly reduced the height of the faba bean crop. [7] reported

Table 3 Interaction effects of faba bean varieties and fungicides on faba bean gall, plant height, and yield components

Variety	Fungicide	DI (%) 94 DAS	PSI (%) 94 DAS	PH (cm)	PP (g)	SPP (t/ha)	HSW (g)	SY (t/ha)	GY (%)	RYL (%)	YIOC (%)
Local	Metalaxyl + Mancozeb	51.43 ^a	30.50 ^c	99.23 ^{cd}	9.50	2.23	39.59 ^{bc}	6.28 ^d	1.74 ^{bc}	32.82	20.83
	Triadimefon	43.23 ^d	26.73 ^{de}	105.33 ^{abcd}	9.60	2.27	41.67 ^{bc}	6.96 ^c	1.74 ^{bc}	32.82	20.83
	Ethylene Bisdithiocarbamate	52.27 ^a	33.17 ^b	93.77 ^{cd}	9.40	2.20	40.07 ^{bc}	5.61 ^e	1.69 ^{cd}	34.75	17.36
	Control	52.77 ^a	35.83 ^a	90.80 ^d	9.03	2.17	38.37 ^c	5.24 ^e	1.44 ^d	44.40	0
Walki	Metalaxyl + Mancozeb	44.53 ^{bc}	22.79 ^f	111.87 ^{abc}	10.03	2.41	44.77 ^{bc}	7.28 ^{bc}	1.95 ^{bc}	24.71	35.42
	Triadimefon	44.77 ^{bcd}	22.71 ^f	126.27 ^a	10.47	2.43	62.23 ^a	9.26 ^a	2.59 ^a	0	79.9
	Ethylene Bisdithiocarbamate	45.37 ^{bcd}	23.59 ^f	109.47 ^{abcd}	9.40	2.30	46.60 ^b	7.29 ^{cb}	1.88 ^{bc}	27.41	30.55
	Control	46.17 ^{bcd}	25.22 ^{def}	104.77 ^{bcd}	9.33	2.27	40.07 ^{bc}	7.00 ^c	1.75 ^{bc}	32.43	21.53
Degaga	Metalaxyl + Mancozeb	43.40 ^d	26.45 ^{de}	107.80 ^{abcd}	9.57	2.30	46.27 ^b	7.28 ^{bc}	1.80 ^{bc}	30.50	25
	Triadimefon	43.40 ^d	24.80 ^{ef}	123.20 ^{ab}	9.83	2.33	55.70 ^a	7.88 ^b	2.02 ^b	22.01	40.28
	Ethylene Bisdithiocarbamate	49.27 ^{abc}	26.61 ^{de}	104.40 ^{bcd}	9.37	2.28	43.77 ^{bc}	7.28 ^{bc}	1.73 ^{cd}	33.20	20.14
	Control	49.83 ^{ab}	27.58 ^d	95.07 ^{cd}	9.23	2.23	38.40 ^c	6.74 ^{cd}	1.71 ^{cd}	33.98	18.75
LSD ($p \leq 0.05$)		5.14	2.53	20.99	–	–	7.78	0.63	0.29		
SL		*	**	*	Ns	Ns	*	*	*		
CV (%)		6.60	5.53	11.75	11.61	7.80	10.52	5.31	9.54		
SE ±		0.98	0.73	2.46	0.17	0.03	0.05	0.18	0.05		

LSD least significant difference, SL significance level, DAS days after sowing, CV Coefficient of variation, SE standard error, PPP Pod per plant, SPP Seed per pod, SY Straw yield, GY Grain yield, RYL Relative yield loss, HSW Hundred seed weight, YIOC Yield increase over control

*significant difference $p \leq 0.05$, ** highly significant difference $p \leq 0.01$, ns = non-significant means with in a column followed by the same letter (s) are not significantly different each other

similar findings, noting a significant difference in the hundred seed weight (HSW) between different varieties and fungicides. Moreover, [9] found variations in seed yield (SY) and grain yield (GY). Lastly, [5] indicated that the highest relative yield loss (RYL) was recorded in plots treated with the control treatment.

Triadimefon appears to reduce the formation of galls in faba beans by impacting essential cellular functions within the pathogen. It inhibits the synthesis of cell membranes by blocking the production of ergosterol and disrupting critical enzymes, which restricts pathogen growth. Additionally, it activates the plant's innate defense mechanisms. This activation may involve initiating systemic acquired resistance or other defense pathways, resulting in the generation of protective enzymes and substances. As a result, the plant becomes more resilient against the attacking pathogen, leading to a decrease in gall formation.

The Walki variety of faba beans may possess specific resistance genes or quantitative trait loci that enhance its ability to withstand gall-forming pathogens. These genes enable the plant to quickly detect invading pathogens and initiate targeted defense responses. Upon detection, the plant may produce elevated levels of defensive compounds, such as phenolics, phytoalexins, and other secondary metabolites. This response activates signaling pathways involving molecules like salicylic acid and jasmonic acid, which lead to localized cell death to help contain the pathogen.

A unique feature of Triadimefon is its ability to target the pathogen while simultaneously boosting the plant's inherent defenses, resulting in more effective control of faba bean gall. The Walki variety employs an integrated defense strategy that combines structural, genetic, and biochemical approaches, limiting gall development and helping to maintain a higher yield.

Fig. 2 Effect of fungicides against faba bean gall disease on faba bean in variety x fungicide trial during 2021 main cropping season



Fig. 3 Reactions of faba bean varieties to faba bean gall disease in variety x fungicide trial during 2021 main cropping season. Keys: **A** galls on the upper side of the leaf at the initial stage, **B** Galls on the underside of the leaf changed to brown, **C** Abnormal leaf growth



Fig. 4 Keys: **A** galls on the upper side of the leaf at the initial stage, **B** Galls on the underside of the leaf changed to brown, **C** Abnormal leaf growth



3.3 Association of disease, yield and yield-related parameters of faba bean

The correlation values indicated a clear association among the parameters related to the crop and the disease, revealing both the strength and direction of these relationships. Analysis of correlation among the percentage disease incidence (PDI), percentage severity index (PSI), area under disease progress curve (AUDPC), disease progress regression (DPR), hundred seed weight (HSW), and grain yield (GY) showed notable differences in associations among various plant varieties treated with fungicides (see Table 4).

PDI, PSI, AUDPC, and DPR exhibited highly significant negative correlations ($p < 0.01$) with GY, with correlation coefficients of $r = -0.511$, $r = -0.554$, $r = -0.547$, and $r = -0.631$, respectively. These correlations indicate a moderate relationship. Additionally, PDI and PSI, PDI and AUDPC, PDI and DPR, PSI and AUDPC, PSI and DPR, as well as AUDPC and DPR were all found to be highly and positively correlated (with coefficients of $r = 0.759$, $r = 0.750$, $r = 0.626$, $r = 0.997$, $r = 0.721$, and $r = 0.735$, respectively; $p < 0.01$).

Furthermore, HSW also demonstrated a highly significant negative association ($p < 0.01$) with PDI ($r = -0.513$), PSI ($r = -0.635$), AUDPC ($r = -0.618$), and DPR ($r = -0.446$) (refer to Table 4).

There was a significant negative correlation ($P < 0.05$) between PDI and PPP ($r = -0.386$), PSI and SPP ($r = -0.406$), as well as AUDPC and SPP ($r = -0.406$). In contrast, a highly significant positive correlation ($P < 0.01$) was found between SPP and GY ($r = 0.495$). Additionally, a significant positive correlation ($P < 0.05$) was observed between PPP and GY ($r = 0.415$) and between HSW and GY ($r = 0.343$). The very strong positive correlation ($r = 0.997$) between PSI and AUDPC indicates that plots (treatments) that were severely infected showed high AUDPC values (see Table 4).

Consequently, the results of this study indicate that the yield of faba beans was largely determined by the severity of faba bean gall disease. This finding is consistent with the conclusion drawn by [39], which stated that increases in disease parameter values were accompanied by a reduction in yield. According to [35], factors that were positively correlated with each other indicated that the yield of faba beans increased as yield-related parameters increased, whereas negatively correlated parameters suggested that yield increased when those parameters decreased.

The regression equation for yield (t ha^{-1}) is expressed as follows: $\text{yield} = -0.025x + 2.970$, with an R^2 value of 32.90% and a p -value of 0.000. This equation indicates that for every 1% increase in disease severity, there is an associated reduction of approximately 0.025 t ha^{-1} in grain yield. The impact of faba bean gall infection, measured as the final severity of yield loss, accounts for 32.9% of the total losses in grain yield, as indicated by the coefficient of determination (R^2). In this equation, the independent variable “ x ” represents the percentage of disease severity (Fig. 4).

3.4 Economic analysis

An economic analysis was conducted to determine the revenues and costs associated with each treatment utilized in the experiment, following the guidelines outlined in [12]. Various expenses were considered, including the costs of seeds, fungicides, the sprayer, and labor for applying the fungicide across the different treatments. The seed costs

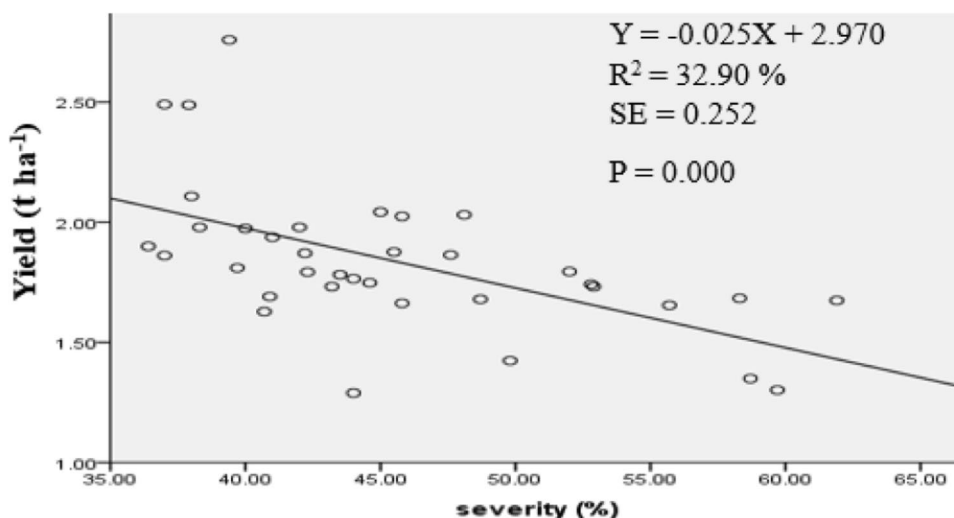
Table 4 Correlation coefficient (r) among disease, yield, and yield-related parameters on faba bean varieties and fungicides during the main cropping season of 2021

Parameters	PDI	PSI	AUDPC	DPR	PPP	SPP	HSW (g)	GY (t ha^{-1})
PDI	1							
PSI	0.759**	1						
AUDPC	0.755**	0.997**	1					
DPR	0.626**	0.721**	0.735**	1				
PPP	-0.386*	-0.281 ^{ns}	-0.279 ^{ns}	-0.303	1			
SPP	-0.259 ^{ns}	-0.406*	-0.406*	-0.452**	0.313	1		
HSW	-0.513**	-0.635**	-0.618**	-0.446**	0.146	0.117	1	
GY	-0.511**	-0.554**	-0.547**	-0.631**	0.415*	0.495**	0.343*	1

PPP Pods per plant, SPP Seeds per pod, HSW hundred seed weight, GY Grain yield, PDI Percentage disease incidence, PSI Percentage severity index, AUDPC Area under disease progress curve, DPR Disease progress rate, ^{ns} non-significant different

* Significant at ($p \leq 0.05$), ** highly significant at ($p \leq 0.01$)

Fig. 5 Linear regressions of grain yield and faba bean gall severity during 2021 main cropping season. x =indicates the disease severity level in percentage, Y =yield, R^2 =coefficient of determination, p =probability SE =standard error



were as follows: Birr 20 per kg for the local variety, Birr 22.5 per kg for the Walki variety, and Birr 21 per kg for the Degaga variety. The labor cost during the season was set at 100 Birr per day.

The selling prices for straw and grain yields in the local market during the harvesting season were Birr 4 per kg and Birr 20 per kg, respectively. For the different treatment combinations, total costs and net benefits were calculated. To determine gross income, yields obtained from each treatment were adjusted by a factor of 10%. All variable costs were aggregated and subtracted from the gross benefits, resulting in net benefits (as shown in Table 5).

The highest net benefits (74,710.4 ETB per hectare) were recorded for the Walki variety treated with Triadimefon. Conversely, the lowest net benefits (40,784 ETB per hectare) were observed for the local variety that received no fungicide treatment (as indicated in Table 5). The results demonstrated that the Walki variety treated with Triadimefon provided substantial benefits at a lower cost compared to other treatments. These findings align with those of [35], which highlighted significant heterogeneity in cost–benefit analyses of fungicides.

To calculate the Marginal Rate of Return (MRR), a dominance analysis was performed by ranking the treatments according to their total variable costs in ascending order. According to reference [12], any treatments with net benefits less than or equal to those of the previous treatment were identified and eliminated from further analysis (see Table 6).

The highest net benefit (number_1 ETB ha⁻¹) with the lowest production cost (5245.6 ETB ha⁻¹) was achieved with the combination of Triadimefon and the Walki variety. This was followed by the Degaga variety treated with Triadimefon (see Table 7). These results are consistent with findings from sources [5, 35, 39], which reported that the application of various fungicides yields a higher net benefit compared to unsprayed plots and provides different rates of return among them.

3.5 Sensitivity analysis and risk identification

Table 8 highlights key variables that affect net returns and benefit–cost ratios in different scenarios involving the integration of the Walki variety and Triadimefon fungicide, which showed the highest marginal rate of return. This analysis helps identify the most important factors influencing profitability, addresses uncertainty, and provides a comprehensive economic assessment to support better decision-making in crop management strategies.

A decrease in grain yield from 2.331 t ha⁻¹ to 2.058 t ha⁻¹ and in straw yield from 8.334 t ha⁻¹ to 7.242 t ha⁻¹ in Scenario 1 results in a reduction of the gross return from 79,956 ETB ha⁻¹ to 70,128 ETB ha⁻¹. This, in turn, lowers the net return from 74,710.4 ETB ha⁻¹ to 64,882.4 ETB ha⁻¹. In Scenario 2, an increase in grain yield from 2.331 t ha⁻¹ to 2.604 t ha⁻¹ and in straw yield from 8.334 t ha⁻¹ to 9.426 t ha⁻¹ boosts the gross return from 79,956 ETB ha⁻¹ to 89,784 ETB ha⁻¹, thereby raising the net return to 84,538.4 ETB ha⁻¹. Scenario 3 sees a decrease in the sale price of grain yield from 20,000 ETB t⁻¹ to 18,811 ETB t⁻¹, as well as in the sale price of straw yield from 4000 ETB t⁻¹ to 3727 ETB t⁻¹. This leads to a reduction in the gross return from 79,956 ETB ha⁻¹ to 74,909.2 ETB ha⁻¹, which subsequently lowers the net return from 74,710.4 ETB ha⁻¹ to 69,663.7 ETB ha⁻¹. Conversely, in Scenario 4, an increase in the sale price of grain yield from 20,000 ETB t⁻¹ to 21,189 ETB t⁻¹ and an increase in the sale price of straw yield from 4000 ETB t⁻¹ to 4273 ETB t⁻¹ raises the gross return from 79,956 ETB ha⁻¹ to 74,909.2 ETB ha⁻¹ and increases the net return from 74,710.4 ETB ha⁻¹ to 69,663.7 ETB ha⁻¹. In Scenario 5, when both fungicide and other costs are raised to 160.6

Table 5 Partial budget analysis for the management of faba bean gall using varieties and fungicides under field conditions during the main cropping season of 2021

No	Cost benefit data	Variety and fungicide treatment combinations											
		L×NF	L×EB	L×T	L×MM	W×NF	W×EB	W×T	W×MM	D×NF	D×EB	D×T	D×MM
1	Adj.GY (t ha ⁻¹) (GY*0.9)	1.296	1.521	1.566	1.566	1.575	1.692	2.331	1.755	1.539	1.557	1.818	1.62
2	Sale ETB (t ⁻¹)	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
3	Sale revenue (ETBha ⁻¹) (1 × 2)	25,920	30,420	31,320	31,320	31,500	33,840	46,620	35,100	30,780	31,140	36,360	32,400
4	Adj.SY (t ha ⁻¹) (SY × 0.90)	4.716	5.049	6.264	5.652	6.30	6.561	8.334	6.552	6.066	6.552	7.092	6.552
5	Sale ETB (t ⁻¹)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
6	Sale revenue (ETBha ⁻¹) (4 × 5)	18,864	20,196	25,056	22,608	25,200	26,244	33,336	26,208	24,264	26,208	28,368	26,080
7	Total Sale Revenue (ETB ha ⁻¹) (3 + 6)	44,784	50,616	56,376	53,928	56,700	60,084	79,956	61,308	55,044	57,348	64,728	58,480
8	Costs of fungicides (ETB ha ⁻¹)	0	315	145.6	331	0	315	145.6	331	0	315	145.6	331
9	Costs of seeds (ETB ha ⁻¹)	4000	4000	4000	4000	4500	4500	4500	4500	4200	4200	4200	4200
10	Costs of spray equipment (ETB ha ⁻¹)	0	193	0	193	0	193	0	193	0	193	0	193
11	Labor cost to apply fungicide (ETB ha ⁻¹)	0	2300	600	2300	0	2300	600	2300	0	2300	600	2300
12	Total variable cost (ETB ha ⁻¹)	4000	6808	4745.6	6824	4500	7308	5245.6	7324	4200	7008	4945.6	7024
13	Net benefit (ETB ha ⁻¹) (7–12)	40,784	43,808	51,630.4	47,104	52,200	52,776	74,710.4	53,984	50,244	49,740	59,182.4	50,856

L local, NF no fungicide, W Walki, D Degaga, MM Metalaxyl + Mancozeb, EB Ethylene Bisdithiocarbamate, T Triadimefon

Table 6 Dominance analysis for faba bean yield as affected by varieties and fungicides during 2021 main cropping season

Treatment combinations	TVC (ETB ha ⁻¹)	NB (ETB ha ⁻¹)	Dominance
Local × No fungicide	4000	40,784	
Degaga × No fungicide	4200	50,244	
Walki × No fungicide	4500	52,200	
Local × Triadimefon	4745.6	51,630.4	Dominated
Degaga × Triadimefon	4945.6	59,182.4	
Walki × Triadimefon	5245.6	74,710.4	
Local × Ethylene Bisdithiocarbamate	6808	43,808	Dominated
Local × Metalaxyl + Mancozeb	6824	47,104	Dominated
Degaga × Ethylene Bisdithiocarbamate	7008	49,740	Dominated
Degaga × Metalaxyl + Mancozeb	7024	50,856	Dominated
Walki × Ethylene Bisdithiocarbamate	7308	52,776	Dominated
Walki × Metalaxyl + Mancozeb	7324	53,984	Dominated

TVC total variable cost, NB net benefit

Table 7 Marginal rate of return (MRR) of faba bean yield as influenced by interaction effect of varieties and fungicides during 2021 main cropping season

Treatment combination	TVC (Birr ha ⁻¹)	NB (Birr ha ⁻¹)	MRR (%)	Rank
Local × No fungicide	4000	40,784	–	
Degaga × No fungicide	4200	50,244	4730	2
Walki × No fungicide	4500	52,200	652	4
Degaga × Triadimefon	4945.6	59,182.4	1567	3
Walki × Triadimefon	5245.6	74,710.4	5176	1

TVC total variable cost, NB net benefit, MRR marginal rate of return

ETB ha⁻¹ and 5396 ETB ha⁻¹ respectively, the total cost becomes 5556.6 ETB ha⁻¹, which reduces the net return to 74,399.4 ETB ha⁻¹. Conversely, in Scenario 6, when costs decrease to 130.6 ETB ha⁻¹ and 4804 ETB ha⁻¹, the net return increases to 75,021.4 ETB ha⁻¹.

The sensitivity analysis revealed that both yield and sale price significantly impact profitability. Even if yield decreases or sale prices fall, the treatment can still generate a positive net return, although it will be lower. If market prices are expected to decline or yields are reduced due to environmental conditions, it is crucial to explore cost-saving strategies or seek additional support to maintain profitability. With minor fluctuations, options such as crop insurance or adjusting input levels may be beneficial.

4 Conclusions and recommendations

4.1 Conclusion

This analysis revealed that the incidence and severity of faba bean gall varied across different treatments. The disease is significant enough to warrant further attention in the study area, as effective control can be achieved economically through the use of fungicides and resistant cultivars. It can also be concluded that integrated disease management is the preferred approach, due to advances in understanding the after-effects of fungicides and the ineffectiveness and unreliability of a single alternative management option.

According to statistics on disease incidence, yield, and yield components, the application of Triadimefon to the Walki variety reduced disease levels and resulted in a higher yield compared to the other treatments. In terms of financial returns, the use of Triadimefon as part of an integrated disease management strategy outperformed the other treatments for the Walki variety.

Table 8 Analysis of sensitivity data under different scenarios from the base values for integrated treatment (Walki variety × Triadimefon fungicide)

Scenario	Grain Yield (t ha ⁻¹)	Sale price ETB (t ⁻¹)	Return (ETB ha ⁻¹)	Straw Yield (t ha ⁻¹)	Sale price ETB (t ⁻¹)	Return (ETB ha ⁻¹)	Gross return (ETB ha ⁻¹)	Fungicide cost (ETB ha ⁻¹)	Other costs (ETB ha ⁻¹)	Total costs (ETB ha ⁻¹)	Net return (ETB ha ⁻¹)
Base	2.331	20,000	46,620	8.334	4000	33,336	79,956	145.6	5100	5245.6	74,710.4
Scenario 1: lower yield	2.058	20,000	41,160	7.242	4000	28,968	70,128	145.6	5100	5245.6	64,882.4
Scenario 2: higher yield	2.604	20,000	52,080	9.426	4000	37,704	89,784	145.6	5100	5245.6	84,538.4
Scenario 3: lower price	2.331	18,811	43,848.4	8.334	3727	31,060.8	74,909.2	145.6	5100	5245.6	69,663.7
Scenario 4: higher price	2.331	21,189	49,391.6	8.334	4273	35,611.2	85,002.7	145.6	5100	5245.6	79,757.1
Scenario 5: increased costs	2.331	20,000	46,620	8.334	4000	33,336	79,956	160.6	5396	5556.6	74,399.4
Scenario 6: decreased costs	2.331	20,000	46,620	8.334	4000	33,336	79,956	130.6	4804	4934.6	75,021.4

4.2 Recommendations

Based on the results of the current study, integration of improved Walki variety with Triadimefon recorded the highest net benefit (74,710.4ETB ha⁻¹) and could be recommended as an immediate option for the management of FBG disease in the study area. However, an extensive similar study should be conducted across main cropping seasons and locations to come up with tangible recommendations.

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Data availability The data supporting this study's findings are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate This research did not involve any human or animal subjects and did not require ethical approval. Not applicable. This study did not involve human participants.

Consent for publication Not applicable. This study does not include any personal data from individuals.

Competing interests The authors declare no competing interests.

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