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Inoculum sources and management of bean scab caused by *Elsinoë phaseoli*

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Abstract

Bean scab caused by *Elsinoë phaseoli* is a major challenge to common bean cultivation in Kenya. However, knowledge about its epidemiology and management is limited. This study conducted three experiments in Kakamega, Kenya, evaluating scab inoculum sources and control options. The first experiment evaluated three different inoculum sources over two seasons; bean crop residue caused the highest scab incidence in both the 2021 (62.1%) and 2022 (81.1%) seasons. The second experiment assessed the effect of rotation history on scab over three seasons. Scab incidence consistently surpassed 90% within the first 30 days after planting in half-yearly rotated fields across all seasons, while the disease was absent after planting in fields with no recent history of legumes. Fields rotated out of legumes consistently had the highest grain yield, averaging 1.5 t ha^{-1} over the seasons. Additionally, the rotation land treatment displayed significantly more pods per plant during the 2021 (9.7), 2022a (9.8), and 2022b (12.5) seasons. In the third experiment, the impact of five fungicides and four cropping systems on bean scab was investigated over two seasons. Neither fungicide treatments nor cropping systems had an effect on bean scab incidence even when only severe symptoms were considered. Carbendazim had the highest yield (1.9 t ha^{-1}) outperforming the unsprayed control only in the 2022 season while none of the other fungicides outperformed the control treatment in yield parameters in either season. This study emphasizes the challenge of managing bean scab without proper crop rotation and underscores the role of crop residue as a critical inoculum source.

KEYWORDS
bean scab, crop rotation, *Elsinoë phaseoli*, inoculum sources, *Phaseolus vulgaris*

1 | INTRODUCTION

The common dry bean (*Phaseolus vulgaris* L.) is the most important pulse for direct human consumption in Kenya. Bacterial, fungal, and viral diseases are important constraints to achieving higher common bean productivity in the country (Muthomi et al., 2007). Most of the focus has been on bacterial diseases such as common bacterial blight (*Xanthomonas axonopodis* pv. *phaseoli*) and halo blight (*Pseudomonas savastanoi* pv. *phaseolicola*); fungal diseases such as anthracnose (*Colletotrichum lindemuthianum*), bean leaf rust

(*Uromyces appendiculatus*), and angular leaf spot (*Pseudocercospora griseola*); and viral diseases such as bean common mosaic diseases (Parker et al., 2023). Bean scab is an overlooked and yet one of the most destructive common bean diseases with yield losses of up to 100% (Allen et al., 1996; Phillips, 1995). Common symptoms of bean scab include ashy grey to brown scabby lesions on upper surfaces of the leaves, on the stem, and on the pods, as well as leaf curling, stem and pod twisting. The causal agent of bean scab in Kenya has been identified as the ascomycete *Elsinoë phaseoli* (Masheti et al., 2024). In addition to common beans, *E. phaseoli* has been reported to cause disease in cowpea (*Vigna unguiculata*), lima bean (*Phaseolus lunatus*), runner bean (*Phaseolus coccineus*), and hyacinth bean (*Lablab* sp.) (Fan et al., 2017). This disease can be particularly severe, causing issues such as pod abortion, curvature, and poorly developed grains. Other plant pathogenic *Elsinoë* species include *E. calopoginii* which causes scab on wild groundnut (calopo) in Brazil, *E. fawcettii* and *E. australis* which cause citrus scab (Hyun et al., 2009), *E. pyri* which causes pear and apple spots (Scheper et al., 2013), *E. ampelina* the causal organism of grapevine anthracnose, and *E. perseae* which causes avocado scab (Everett et al., 2010; Li et al., 2018).

It has been demonstrated that the availability of primary inoculum and the presence of susceptible host are important factors in the occurrence of scab diseases (Carisse & Lefebvre, 2011; Carisse & Provost, 2024; Ji et al., 2021). Management programmes against *Elsinoë* spp. that included crop residue removal reduced disease development compared with the standard programme without residue removal, with fewer fungicide applications needed. Major outbreaks of grapevine anthracnose have been observed to occur when there is good synchrony between the availability of *E. ampelina* inoculum and the presence of susceptible host tissue (Carisse & Lefebvre, 2011). Gabel and Tiffany (1987) observed that conidia produced from stromata on partially decomposed and scattered leaf residue served as the primary source of *E. panici* inoculum. In a study to investigate the management of grapevine anthracnose caused by *E. ampelina* in order to reduce the need for fungicides, Carisse and Provost (2024) found that anthracnose was less severe on grapevine when leaves were removed from the vineyards.

Although various types of fungicides, such as protectant copper-based fungicides and systemic fungicides such as carbendazim, are known to control certain *Elsinoë* species, some species such as *E. fawcettii* are known to develop fungicide resistance (Chung, 2011; Smith et al., 2016). In a study on managing avocado purple blotch disease caused by *E. perseae* using fungicides, Esquivel-Miguel et al. (2023) found that copper oxychloride exhibited notable mycelium inhibition on *E. perseae* isolates. Among chemical fungicides, azoxystrobin + propiconazole and thiabendazole displayed consistent and strong inhibition of mycelium growth over a 3-month period. Research on citrus scab caused by *E. fawcettii* found that a one percent Bordeaux mixture and a ten percent extract of holy basil (*Ocimum sanctum*) were effective in inhibiting the pathogen's growth (Bulbule et al., 2016).

In general, there is limited information on bean scab including important information on how the causal agent is transmitted, its survival between seasons, and its reaction to possible control measures such as the use of chemicals and altering of cropping practices. Most of the information available on important aspects of the epidemiology of *E. phaseoli* is derived from information available on other common bean pathogens or plant diseases caused by members of the genus *Elsinoë*. Control methods that have been successful in the control of diseases caused by other *Elsinoë* spp. might be applicable for *E. phaseoli*. As is the case with other diseases, sustainable scab management should be focused on a systems approach that incorporates various components of its epidemiology (Ahmed et al., 2016; Eshetu et al., 2018; Mengesha & Yetayew, 2018). This study builds on Masheti et al. (2024), the first to report *Elsinoë phaseoli* causing scab on common beans in Kenya. The research aims to develop management strategies for bean scab by investigating potential inoculum sources, the impact of cropping history, and the effects of various fungicides and cropping systems on disease progression.

2 | MATERIALS AND METHODS

2.1 | Assessment of bean scab inoculum source

An investigation to assess the origins of bean scab inoculum was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO), Non-Ruminant Research Institute in Kakamega (latitude: 0.2780583° N, longitude: 34.7636944° E, altitude of 1500 m above sea level with annual rainfall of 1200–2200 mm) in Western Kenya (Jaetzold et al., 2005). The experiment spanned two consecutive bean planting seasons (2021 and 2022) and was structured in a completely randomized design. It featured nine 1 × 1-metre micro-plots, each surrounded by wooden borders and filled with forest soil that was sterilized by steaming for 5 h. The sterilized soil was then placed in the plots to a depth of 20 cm. Three distinct treatments (in three replicates) were implemented using *P. vulgaris* 'GLP 2', a variety susceptible to bean scab. These treatments comprised clean seeds of *P. vulgaris* 'GLP 2' planted in sterile soil, farm-saved seeds of *P. vulgaris* 'GLP 2' acquired from previously scab-infested bean fields and planted in sterile soil, and clean seeds of *P. vulgaris* 'GLP 2' cultivated in soil mixed with bean crop residue. For the crop residue treatment, approximately 50 g of unground residue, consisting of a mixture of bean plant parts and soil, was collected from the surface of a field with a recent scab infestation and evenly distributed on the surface of the plots before sowing the seeds. The micro-plots were positioned at least 2 m apart from each other. Each plot had 30 bean seeds planted in three rows with 10 cm intra-row spacing and 50 cm inter-row spacing.

The study was carried out in a partially enclosed screenhouse situated away from other legume crops and shielded by surrounding buildings and structures to mitigate the impact of strong direct winds while maintaining natural weather conditions (Figure 1). Crop management involved a single application of di-ammonium phosphate at a rate of 200 kg ha^{-1} immediately after emergence. Subsequently, the plots received a spray of 50 g L^{-1} lambda-cyhalothrin (Karate Zeon 5

FIGURE 1 Evaluation of bean scab inoculum. (a) Open screenhouse. (b) Wooden frame micro-plots (1×1 m) inside the open screenhouse.

CS, Syngenta) immediately after the hypocotyl emerged (6–8 days after planting) to control bean fly (*Ophiomyia phaseoli*). Weeds were removed manually whenever they appeared. Data collected from the plots included crop emergence and disease incidence. Emergence was evaluated 10 days after planting (DAP), considering the total number of plants per plot. Disease incidence, indicating the percentage of plants displaying scab symptoms in a plot, was recorded at 14 DAP.

2.2 | Field history analysis

The second experiment involved a field trial conducted across two sites at the KALRO, Kakamega, Non-Ruminant Research Station, spanning three consecutive cropping seasons (2021 [short-rain], 2022a [long-rain], and 2022b [short-rain] seasons). The trial followed a randomized complete block design with three replicates. The first site comprised fields with a recent history of common bean (half-yearly rotated), while the second site included fields that had not grown legumes in the preceding 3-year period, henceforth referred to as non-legume fields. Susceptible *P. vulgaris* 'GLP 2' was planted at each site in four rows of 3 m length, with inter- and intra-row spacing of 50×10 cm, resulting in a plot size of 1.5×3 m. There was a 0.5 m spacing from one replicate to the next, leading to a trial size of 5.5×3 m for each site. Three guard rows spaced at 0.5 m surrounded the plots.

Fertilizer application and bean fly control were conducted following the procedures outlined in the bean scab inoculum source evaluation section. Weed control involved manual cultivation every 4 weeks. Collected data included crop emergence, disease incidence, number of pods per plant, number of seeds per pod, and plot weight. Emergence data was recorded as detailed above. Disease data was collected at 7-day intervals from the central two rows of the four-row plots. Data collection spanned from 10 DAP until the point where incidence exceeded 90%. Subsequently, the collected incidence data was used to determine the final incidence (incidence at the last interval), mean scab incidence (average incidence across intervals), and area under the disease progress curve (AUDPC) based on percent disease incidence (Ahmed et al., 2016).

The number of pods per plant was determined by counting and averaging the number of pods on 10 randomly selected plants within a plot. Similarly, the number of seeds per pod was obtained by counting and averaging the number of seeds from 10 pods randomly selected from individual plants. Harvesting occurred when the crops reached maturity, and after harvest the plants were sun-dried before undergoing manual threshing. The plot weight was then measured as the dry weight of seeds obtained from the plot, subsequently converted to yield in tons per hectare.

2.3 | Fungicide and cropping system analysis

A third field trial was executed at the KALRO, Kakamega, Non-Ruminant Research Station, spanning two consecutive cropping seasons (2021 and 2022). The trial adopted a randomized split-plot design featuring six main plots and four sub-plots, replicated four times in the 2021 season and three times in the 2022 season. The main plot treatments focused on fungicide applications, while the sub-plot treatments were dedicated to various cropping systems for bean cultivation.

Fungicides were systematically applied every 7 days, commencing from 14 days after emergence (DAE) until the initiation of pod filling. The selection of fungicides was based on their active ingredients and local market availability for use on beans or other legumes. The fungicides included mancozeb 80% (Oshothane, Osho Ltd.) at 2.5 g L^{-1}, propineb 70%+cymoxanil 6%+crystalline quartz >0.1–<10% (Milraz, BAYER) at 2 g L^{-1}, carbendazim (Rodazim, Rotam) at 1 mL L^{-1}, copper oxychloride 85% (Samaya, Murphy Chemical East Africa Ltd.) at 2.5 g L^{-1}, and metalaxyl-M 40 g kg^{-1}+mancozeb 640 g kg^{-1} (Ridomil, Syngenta) at 2.5 g L^{-1}. The application concentrations were based on product label recommendations. Non-spray plots were employed as control. The application method utilized a knapsack sprayer with a 20-L capacity, delivering a standard rate of 1000 L of mixture per hectare.

The sub-plot treatments comprised four primary common bean cropping systems employed by farmers in Kenya. These treatments encompassed the cultivation of *P. vulgaris* 'GLP 2' under mixed-cropping (intercrop), in a pure stand with expanded spacing (spacing), and in a mixed variety, as well as a pure stand (control) with recommended spacing. In the mixed-crop system, *P. vulgaris* 'GLP 2' was intercropped with maize. In the spacing treatment, it was planted in a pure stand with inter- and intra-row spacing of 50 and 15 cm, respectively. For the mixed variety treatment, *P. vulgaris* 'GLP 92' (resistant) and *P. vulgaris* 'GLP 2' (susceptible) were thoroughly mixed in equal proportions. In the pure stand (standard practice/control), *P. vulgaris* 'GLP 2' was planted with respective inter- and intra-row spacing of 50 and 10 cm.

All sub-plots were standardized to measure 5×3 m, each containing 5-m-long rows. Pure stand, spacing, and mixed variety treatments consisted of seven rows each, with an inter-row spacing of 0.5 m. In the case of intercropping maize and *P. vulgaris* 'GLP 2', they shared the same row, with intra-row spacing set at 30 and 10 cm, respectively, and an inter-row spacing of 0.75 m, resulting in a total of five rows. Pure stand and mixed variety treatments featured an intra-row spacing of 10 cm between plants, while spacing treatment maintained a 15 cm distance between plants. A 0.5-m space separated the sub-plots, leading to main plot dimensions of 10.5×6.5 m for each fungicide treatment. The main plots were further isolated from each other by a 2-m spacing, resulting in a total block size of 23×23.5 m for each replicate. The 2-m spacing between main plots was maintained free of weeds, and each replicate was bordered by a guard row along the outer borders.

Natural bean scab development was encouraged by siting the trial in fields with a recent history of common bean crops affected by scab, following the seasonal (half-yearly) rotation practices of local farmers in the region. Crop management adhered to the procedures described in the section on bean scab inoculum sources. Disease incidence data collection was consistent with the guidelines provided in the field history section. The scale for rating bean scab severity was developed in this study, as no existing scale covered bean scab symptoms in detail. It was based on the categorization of bean scab symptoms, where: 0 = Disease absence from the field; 1 = No visible symptom on a plant or normal-shaped leaves and pods with minute un-coalesced scab spots, less than 2 mm long lesions on stems and leaf veins; 2 = Deformity: Leaf curling and stem twisting, raised, coalesced scab lesions on pods and stems; 3 = Necrosis and Death: Leaf necrosis and defoliation, stems, and pods completely covered with scab pustules, severe stem or pod twisting, pod mummification (Figures 2–4). Disease data were collected at 15-day intervals during the vegetative stage (at 30 DAP), flowering stage (at 45 DAP), and pod-filling stage (at 70 DAP) of *P. vulgaris* 'GLP 2'.

2.4 | Data analysis

Data analysis for all experiments utilized R (R Core Team, 2021). Treatment effects were determined using linear regression, ANOVA, and post hoc tests with the Sidak adjustment. R packages such as dplyr, lme4, and ggplot2 facilitated data handling, modelling, and visualization. Statistical comparisons were conducted at a 95% confidence level using the Kenward-Roger approximation (Lenth, 2023).

3 | RESULTS

3.1 | Assessment of bean scab inoculum source

The treatments involving different inoculum sources demonstrated significant effects ($p < .05$) on the incidence of bean scab and emergence of *P. vulgaris* 'GLP 2' during both the 2021 and 2022 seasons (Table 1). In the 2021 season, the field residue treatment yielded the highest scab incidence at 62.1%, a figure significantly ($p \le .05$) higher than both the clean seed and farm-saved seed treatments, which exhibited no scab symptoms. Additionally, farm-saved seeds displayed the lowest emergence percentage during this season, registering at 26.7%, a value significantly lower than both the field residue and clean seed treatments. During the 2022 season, the field debris treatment exhibited the highest incidence of bean scab at 81.1%, a figure significantly surpassing all other treatments. In contrast, the clean seed and farm-saved seed treatments recorded the lowest disease incidence values at 0 and 5.6%, respectively. Furthermore, the field residue treatment displayed the lowest plant emergence in the 2022 season, standing at 70.0%, a value significantly lower than the clean seed treatment, which boasted the highest emergence at 86.7%.

3.2 | Field history analysis

Scab incidence in the half-yearly rotated fields consistently exceeded 95% within 30 DAP, with notably high incidence values of 97.0, 94.6, and 99.1% in the 2021, 2022a, and 2022b seasons, respectively (Figure 5). The analysis detected significant differences in scab incidence and AUDPC in each individual season with non-legume fields consistently showing no bean scab symptoms (Table 2). Additionally, the half-yearly rotated fields had significantly lower emergence in the 2021 and 2022a seasons (36.7 and 47.3%, respectively) compared with the corresponding seasons of the non-legume field treatment, which had emergence percentages of 58.0% and 63.7%, respectively. However, there was no significant difference in emergence between the treatments in the 2022b season. Although the seasons did not significantly affect the final scab incidence in the half-yearly fields, they did have a significant impact on the average incidence and AUDPC (Table 3). Notably, the 2022b season displayed the highest average disease incidence (71.1%) and AUDPC (1455 percent-days).

While seasons did not exert a significant effect on yield, the number of pods per plant, and the number of seeds per pod, the impact of field cropping history on these components was evident in the analysis (Table 4). The non-legume field treatment had average grain yields of 1.4, 1.7, and 1.5 t ha^{-1} in the 2021, 2022a, and 2022b seasons, respectively. These yields surpassed the half-yearly rotated treatments, which consistently yielded 0.1 t ha^{-1} across all three seasons. Additionally, the non-legume field treatment showed a significantly higher number of pods per plant, with 9.7, 9.8, and 12.5 pods/plant in the 2021, 2022a, and 2022b seasons, respectively. In contrast, the half-yearly rotated fields had only about one pod per plant in the corresponding seasons (Table 4). However, there were no significant differences in the number of seeds per pod between the non-legume field and half-yearly rotated fields in any of the seasons.

3.3 | Fungicide and cropping system analysis

Scab symptoms were ubiquitous in the field within 30 DAP in both 2021 and 2022 seasons, and the analysis therefore focused on

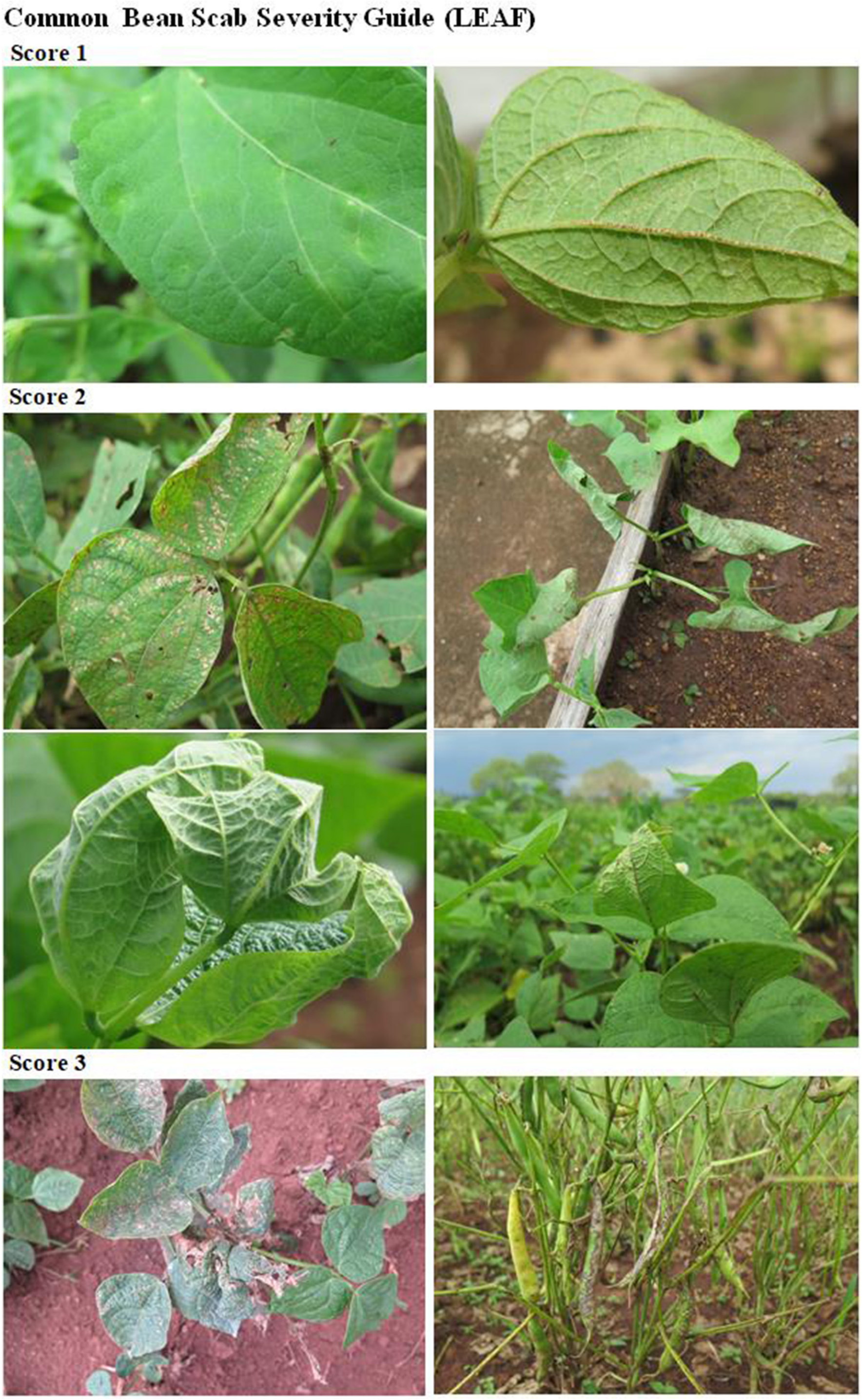

FIGURE 2 Severity scale for scab (caused by *Elsinoë phaseoli*) on bean leaves.

severity scores falling within the range of 2 to 3, as outlined in the categorization of bean scab symptoms severity in the Materials and Methods section. In the combined analysis, neither fungicide nor cropping systems showed significant effects on bean scab final severity (FS), mean severity (MS), or AUDPC. In individual season analysis, the cropping system treatments had no significant ($p < .05$) impact on bean scab FS, MS, and AUDPC in both seasons. Fungicide treatments had no significant impact on scab MS across all seasons, whereas in the 2021 season, they significantly influenced AUDPC, with the control treatment recording the lowest AUDPC at 962 percent-days (Table 5). In the 2022 season, fungicides had a significant effect on both scab FS and AUDPC, with the control treatment again displaying the lowest FS (8.9%) and the lowest AUDPC (372 percent-days).

In the combined season analysis, neither the fungicide treatments nor the cropping systems exhibited statistically significant differences in yield or yield components when compared with their respective control treatments. Although fungicide spray treatments showed no significant effects in the 2021 season, they did have a significant impact on yield, the number of pods per plant, and the

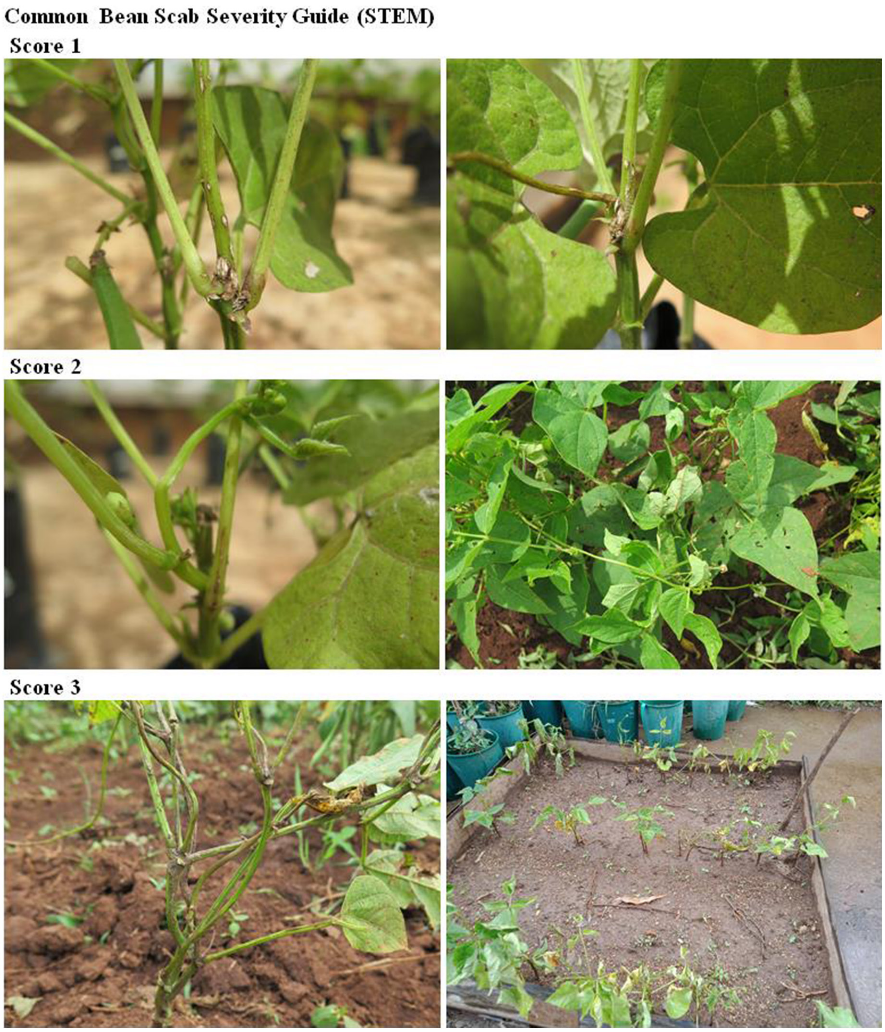

FIGURE 3 Severity scale for scab (caused by *Elsinoë phaseoli*) on bean stems.

number of seeds per pod in the 2022 season (Table 6). Specifically, during the 2022 season, carbendazim-treated plots achieved the highest yield, with 1.9 t ha^{-1}, as well as the greatest number of pods per plant (9.3) and seeds per pod (4.6). Carbendazim outperformed the control treatment only in terms of yield in the 2022 season, while none of the other fungicide treatments significantly outperformed the control treatment in yield, number of pods, or number of seeds in either the 2021 or 2022 seasons (Table 6).

Although the cropping system treatments did not demonstrate significant effects on yield and yield components in the 2021 season, they did have a significant impact on yield and the number of pods per plant in the 2022 season (Table 7). Specifically, in the 2022 season, the spacing treatment demonstrated the lowest yield and number of pods per plant with 0.9 t ha^{-1} and 6.4 pods per plant respectively. On the other hand, the pure stand treatment (control) performed the best in terms of yield, with a yield of 1.3 t ha^{-1} (Table 7).

4 | DISCUSSION

The presence of scab-infested field debris in the semi-controlled experiment resulted in high levels of bean scab incidence, indicating that it serves as the primary source of *E. phaseoli* inoculum. Due to limited literature on *E. phaseoli* epidemiology, assumptions were derived from information on relatable bean pathogens or diseases on other hosts caused by *Elsinoë* spp. Plant residue acting as a source of inoculum has also been documented in other *Elsinoë* species (Ji et al., 2021). Gabel and Tiffany (1987) observed that while *E. panici* did not colonize dead plant parts, conidia produced from stromata on partially decomposed and scattered leaf litter served as the primary inoculum.

Although the role of seed-borne inoculum was not fully explored in this study, the poor emergence of farm-saved seeds in the 2021 season suggests that *E. phaseoli* negatively affects seed viability. When the emergence of farm-saved seeds improved in 2022, it showed some scab incidence, implying that the pathogen may be seed-transmitted. The cultivation of seeds from infected plants might be linked to poor emergence and appearance of scab symptoms on the cultivar. It is feasible that *E. phaseoli* relies on plant residue as its primary means of spread while also being seed-transmitted. The fungus *C. lindemuthianum*, which causes bean anthracnose, is an example of a pathogen known to be transmitted through both infested plant residues and seeds (Yusuf & Sangchote, 2005). Previous research has demonstrated

FIGURE 4 Severity scale for scab (caused by *Elsinoë phaseoli*) on bean pods.

TABLE 1 Mean percent emergence and incidence of bean scab (caused by *Elsinoë phaseoli*) on *Phaseolus vulgaris* 'GLP 2' with different inoculum sources in the 2021 short-rain and 2022 long-rain seasons, Kakamega, Kenya.

	2021		2022	
Treatment	Emergence (%)	Incidence (%)	Emergence (%)	Incidence (%)
Field residue	88.9a	62.1a	70.0b	81.1a
Clean seed	78.9a	0.0b	86.7a	0.0b
Farm-saved seed	26.7b	0.0b	78.9ab	5.6b
Mean	64.8	20.7	78.5	30.8
Average SE	5.17	4.02	3.57	3.32

Note: SE = standard error of differences; for mean comparisons, the Sidak adjustment method was employed. Treatments with the same letters in the same column indicate no significant differences at $p < .05$. The Kenward-Roger method was utilized for degrees of freedom, while the Sidak method was applied for confidence-level and p value adjustment.

that seed-borne fungal pathogens can reduce germination and emergence in beans (Marcenaro & Valkonen, 2016). Certain fungal pathogens can infect developing seeds in the field without causing symptoms and later destroy seedlings (Batzer et al., 2022). Seeds are believed to become infected when the pathogen is transmitted from diseased young pods through the vascular system to the seed (Torres et al., 2009).

Bean scab was completely absent when clean seed of *P. vulgaris* 'GLP 2' was cultivated in land that had not grown legumes in the preceding 3-year period, but was ubiquitous within 30 DAP when cultivated on land rotated half-yearly, indicating that a 6-month rotation period is insufficient to suppress the pathogen. Insufficient crop rotation is a known cause of increased and earlier occurrence of fungal diseases in field crops (Juroszek & von Tiedemann, 2011). This study

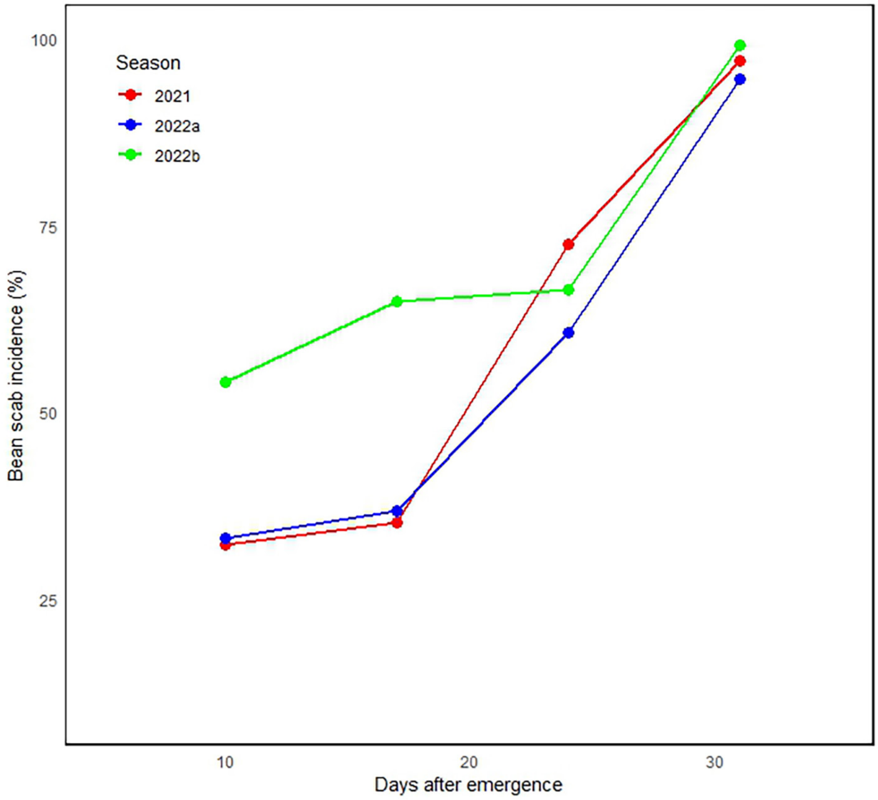

FIGURE 5 Progress of bean scab incidence (caused by *Elsinoë phaseoli*) on *Phaseolus vulgaris* 'GLP 2' in half-yearly rotated fields during the 2021, 2022a, and 2022b seasons.

TABLE 2 Percent emergence and disease parameters of bean scab (caused by *Elsinoë phaseoli*) on *Phaseolus vulgaris* 'GLP 2' cultivated in non-legume and half-yearly rotated fields for three cropping seasons, Kakamega, Kenya.

	2021			2022a			2022b		
Treatment	EM (%)	INC (%)	AUDPC (percent-days)	EM (%)	INC (%)	AUDPC (percent-days)	EM (%)	IN (%)	AUDPC (percent-days)
Non-legume	58.0b	0.0a	0.0a	63.7b	0.0a	0.0a	59.7a	0.0a	0.0a
Rotation	36.7a	97.0b	1207b	48.3a	94.6b	1130b	50.3a	99.1b	1455b
Mean	47.3	48.5	603.5	56	47.3	565	55	49.5	727
SE	3.78	6.36	81.7	3.78	3.4	39.1	3.78	4.59	57.7

Note: SE = Standard error of differences; for mean comparisons, the Sidak adjustment method was employed. Treatments with the same letters in the same column indicate no significant differences at $p < .05$. The Kenward-Roger method was utilized for degrees of freedom, while the Sidak method was applied for confidence-level and p value adjustment.

Abbreviations: AUDPC, area under disease progress curve; EM, emergence; INC, disease incidence.

TABLE 3 Disease parameters of bean scab (caused by *Elsinoë phaseoli*) on *Phaseolus vulgaris* 'GLP 2' cultivated in half-yearly rotated fields for three cropping seasons in Kakamega, Kenya.

	Disease parameter			
Season	Final incidence (%)	Mean incidence (%)	AUDPC (percent-days)	Progress rate (%)
2021	97.0a	59.3a	1207a	209a
2022a	94.6a	56.3a	1130a	198a
2022b	99.1a	71.1b	1455b	145b
Mean	96.5	62.2	1264	184
SE	1.4	2.1	51.3	9.0

Note: SE = Standard error of difference; for mean comparisons, the Sidak adjustment method was employed. Treatments with the same letters in the same column indicate no significant differences at $p < .05$. The Kenward-Roger method was utilized for degrees of freedom, while the Sidak method was applied for confidence-level and p value adjustment.

TABLE 4 Mean yield and yield components of *Phaseolus vulgaris* 'GLP 2' cultivated in non-legume and half-yearly rotated fields for three cropping seasons, Kakamega, Kenya.

	2021			2022a			2022b		
Treatment	**Yield ($t\,ha^{-1}$)**	**Number of pods**	**Number of seeds**	**Yield ($t\,ha^{-1}$)**	**Number of pods**	**Number of seeds**	**Yield ($t\,ha^{-1}$)**	**Number of pods**	**Number of seeds**
Non-legume	1.4b	9.7b	4.0a	1.7b	9.8b	6.9a	1.5b	12.5b	4.2a
Rotation	0.1a	1.0a	1.8a	0.1a	1.2a	4.1a	0.1a	1.1a	1.5a
Mean	0.8	5.4	2.9	0.9	5.5	5.5	0.8	6.8	2.9
SE	0.11	1.05	2	0.11	1.05	2	0.11	1.05	2

Note: SE = Standard error of differences; for mean comparisons, the Sidak adjustment method was employed. Treatments with the same letters in the same column indicate no significant differences at $p < .05$. The Kenward-Roger method was utilized for degrees of freedom, while the Sidak method was applied for confidence-level and *p* value adjustment.

TABLE 5 Mean disease parameters of bean scab (caused by *Elsinoë phaseoli*) on *Phaseolus vulgaris* 'GLP 2' sprayed with different fungicides for two cropping seasons, Kakamega, Kenya.

	2021			2022		
Fungicide	**FS (%)**	**MS (%)**	**AUDPC**	**FS (%)**	**MS (%)**	**AUDPC**
Carbendazim	37.5a	31.6a	1131ab	27.3ab	27.6a	1090abc
Copper oxychloride 85%	48.9a	44.0a	1822b	24.9ab	20.6a	932ab
Mancozeb 80%	40.9a	31.1a	1449ab	46.1b	31.9a	1583bc
Metalaxyl-M + Mancozeb	40.1a	34.7a	1242ab	26.1ab	23.1a	973ab
Propineb 70%	43.1a	45.2a	1686ab	49.1b	46.8a	1980c
Control	27.8a	27.4a	962a	8.5a	8.9a	372a
Mean	39.7	35.7	1382	30.3	26.5	1155
Average SE	5.86	5.3	172	6.45	5.9	219

Note: SE = Standard error of differences; for mean comparisons, the Sidak adjustment method was employed. Treatments with the same letters in the same column indicate no significant differences at $p < .05$. The Kenward-Roger method was utilized for degrees of freedom, while the Sidak method was applied for confidence-level and *p* value adjustment.

Abbreviations: AUDPC, area under disease progress curve; FS, final disease severity; MS, mean severity.

TABLE 6 Mean yield and yield components of *P. vulgaris* 'GLP 2' sprayed with different fungicides for two cropping seasons, Kakamega, Kenya.

	2021			2022		
Fungicide treatment	**Yield ($t\,ha^{-1}$)**	**Number of pods**	**Number of seeds**	**Yield ($t\,ha^{-1}$)**	**Number of pods**	**Number of seeds**
Carbendazim	0.3a	1.9a	2.6a	1.9c	9.3c	4.6c
Copper oxychloride	0.2a	2.1a	2.2a	1.1ab	7.0abc	4.0bc
Mancozeb 80%	0.2a	2.2a	2.3a	0.6a	5.1a	3.0a
Metalaxyl-M + Mancozeb	0.2a	1.9a	2.4a	1.0ab	6.6abc	3.8abc
Control	0.2a	1.9a	2.3a	1.3b	8.3bc	4.2bc
Propineb 70%	0.3a	2.0a	2.4a	0.8ab	5.8ab	3.6ab
Mean	0.2	2	2.4	1.1	7	3.9
SE	0.1	0.6	0.2	0.1	0.6	0.2

Note: SE = Standard error of differences; for mean comparisons, the Sidak adjustment method was employed. Treatments with the same letters in the same column indicate no significant differences at $p < .05$. The Kenward-Roger method was utilized for degrees of freedom, while the Sidak method was applied for confidence-level and *p* value adjustment.

further highlighted the challenge of controlling bean scab in the absence of sufficient crop rotation as scab incidence was found to be 100% across all fungicide and cropping system treatments. This has been observed on susceptible varieties in South Africa, where scab incidence reached as high as 80% on *P. vulgaris* 'Umlazi' and 100% on *P. vulgaris* 'Umvoti' (Phillips, 1994).

Further research on *E. phaseoli* is urgently needed to explore ways of achieving sufficient levels of reduced inoculum. For instance,

TABLE 7 Mean yield and yield components of *Phaseolus vulgaris* 'GLP 2' cultivated under different cropping systems for two cropping seasons.

	2021			2022		
Cropping	Yield (t ha^{-1})	No pods	No seeds	Yield (t ha^{-1})	No pods	No seeds
Intercrop	0.2a	2.0a	2.2a	1.1ab	6.9ab	4.1a
Pure stand	0.2a	2.0a	2.4a	1.3b	6.7ab	3.7a
Spacing	0.2a	2.0a	2.3a	0.9a	6.4a	3.8a
Variety mix	0.3a	2.1a	2.6a	1.2b	8.1b	3.9a
Mean	0.2	2	2.4	1.1	7	3.9
SE	0.1	0.4	0.1	0.1	0.5	0.2

Note: SE = Standard error of differences; for mean comparisons, the Sidak adjustment method was employed. Treatments with the same letters in the same column indicate no significant differences at $p < .05$. The Kenward-Roger method was utilized for degrees of freedom, while the Sidak method was applied for confidence-level and p value adjustment.

it is crucial to determine the appropriate rotation duration required to decrease inoculum concentration to a level at which other disease management strategies can be effectively incorporated (Carisse & Provost, 2024). When initial *Elsinoe* infections are not properly controlled, an impractically high amount of fungicide is required to prevent severe disease (Hopkins, 1973). Major outbreaks of grapevine anthracnose coincide with the synchrony of initial *E. ampelina* inoculum and susceptible host tissue availability, driving fungicide programmes to target initial inoculum for prevention of secondary infection (Carisse & Lefebvre, 2011).

The impact of fungicide treatments on scab showed inconsistency, possibly influenced by factors unrelated to the treatments. For instance, in both 2021 and 2022, the control treatment exhibited the lowest AUDPC and notably the lowest final disease severity in 2022. Importantly, while these treatments did not effectively reduce bean scab incidence, they successfully maintained other fungal diseases at extremely low levels, often eliminating them entirely. Conversely, the control treatment had a high incidence of other fungal diseases, including angular leaf spot (*P. griseola*) and leaf rust (*U. appendiculatus*). This raises the possibility of pathogen interaction effects, such as angular leaf spot masking scab symptoms or competitive exclusion of scab from the host. Gold et al. (2009) noted that established host infections can inhibit later pathogen incursions, and multi-pathogen competition, driven by limited host resources, may impact epidemics (Jonkers et al., 2012; Perefarres et al., 2014). The balance between host defence and pathogen virulence determines whether a plant-microbe interaction becomes pathogenic (Abdullah et al., 2017). Consequently, the susceptibility of *P. vulgaris* 'GLP 2' to *E. phaseoli* and the use of insufficiently rotated fields might be the reason for the failure of the evaluated management options to control bean scab, even though the field disease history also included other fungal diseases that were effectively controlled in this study. The importance of host resistance and inoculum source in fungal crop disease control has been reported in other studies (Ahmed et al., 2016; Chung, 2011). Researchers have explored genetic resistance against *E. phaseoli* in cowpea highlighting the importance of identifying and utilizing resistant cultivars to mitigate scab-related losses (Barreto et al., 2001; Phillips, 1995).

The fungicides used in this study, such as protective copper-based fungicides, are known to control certain species in *Elsinoë* (Chung, 2011; Esquivel-Miguel et al., 2023). Their failure to control scab in this study might have been due to high amounts of primary inoculum in the fields. Many residue-borne plant diseases can be managed through crop rotation and other agronomic practices designed to reduce inoculum levels and decrease the carry-over of inoculum between cropping seasons (Melloy et al., 2010). For *E. ampelina*, fungicide application is combined with sanitation-based practices, which involve pruning and destroying diseased cane parts and eliminating wild grapes (Carisse & Lefebvre, 2011). Furthermore, the practice of burning fields to eliminate residue from previous crop seasons and reduce primary inoculum has historically proven effective in managing *E. panici* (Gabel & Tiffany, 1987). However, it is worth noting that field burning is currently discouraged due to concerns about air quality. Nevertheless, this practice underscores the critical importance of reducing inoculum in disease control. Fungicide resistance is a recognized characteristic in *Elsinoë* species, including *E. fawcettii* (Chung, 2011; Smith et al., 2016). Therefore, it is valuable to explore whether the elevated bean scab incidence and the absence of an impact on AUDPC might be attributed to heightened pathogen resistance against the employed fungicides.

In addition, the cropping systems evaluated in this study are known to be effective in controlling fungal pathogens in common bean. For example, intercropping beans with cereals is effective in controlling rust, while variety mixtures have been shown to significantly reduce angular leaf spot in beans (Eshetu et al., 2018; Mengesha & Yetayew, 2018; Olango et al., 2016). Mixed-host crop effects mimic the heterogeneity of plant communities, which affects disease dynamics by altering the host density, wind speed, vector spread, and microclimate (Boudreau, 2013; Schoeny et al., 2010). Similar mechanisms could also explain the effectiveness of these treatments in controlling other diseases in this study. The study underscores the significance of bean scab as a disease affecting common bean crops, as evidenced by the substantial reductions in both yield and yield components when scab infection occurred. These findings align with similar outcomes reported by Barreto et al. (2001)

in the case of cowpea plants susceptible to *E. phaseoli* in northeastern Brazil. In that context, scab-infected plants exhibited delayed flowering and maturation, diminished pod length, a reduced number of grains per pod, lower weight per 100 grains, and consequently, a decrease in grain yield.

The environment influenced average disease occurrence and AUDPC in half-yearly rotated fields. The development of a disease is contingent upon favourable environmental conditions, including temperature, humidity, and sunshine hours (Ahmed et al., 2016; Bharti et al., 2019; Eshetu et al., 2018). These conditions, when coupled with inadequate cultural practices such as the absence of crop rotation and the use of infected seeds, can significantly amplify the establishment of a disease (Aytenfsu et al., 2019). Members of the *Elsinoë* genus, including *E. ampelina*, have been observed to be sensitive to temperature variations (Carisse & Lefebvre, 2011; Li et al., 2018). Recognizing the pivotal role of field hygiene in bean scab control, it becomes imperative to raise awareness and provide support to smallholder farmers for the adoption of extended rotation cycles or alternative strategies such as employing disease-resistant varieties, which can effectively mitigate disease risks. Nevertheless, the constraints associated with small farm sizes and a primary focus on subsistence farming pose challenges to the implementation of longer rotation periods by farmers. Hence, further research is needed to explore comprehensive and integrated scab management solutions. These may encompass defining optimal rotation periods, assessing fungicide effects in *E. phaseoli*, and developing common bean varieties with resistance to scab.

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CONFLICT OF INTEREST STATEMENT

The author(s) declare no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

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

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