PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(1): 1-9
https://doi.org/10.14719/pst.6764

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RESEARCH ARTICLE

Quantifying the economic impact and management strategies for foot rot (*Phytophthora capsici* L.) disease on black pepper cultivation in West Coast India: Farm-level insights

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OPEN ACCESS

ARTICLE HISTORY
Received: 18 December 2024
Accepted: 15 January 2025
Available online
Version 1.0 : 24 February 2025
Version 2.0 : 28 February 2025

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
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CITE THIS ARTICLE
Bhat S, Arunachalam V, Paramesha V, Gaonkar N. Quantifying the economic impact and management strategies for foot rot (*Phytophthora capsici* L.) disease on black pepper cultivation in West Coast India: Farm-level insights. Plant Science Today. 2025; 12(1): 1-9. https://doi.org/10.14719/pst.6764

Abstract

Foot rot disease, caused by the soil-borne fungus *Phytophthora capsici*, poses a severe threat to black pepper cultivation, particularly in the Western Ghats region of India. The current study aims to comprehensively assess the economic impact of foot rot disease on black pepper cultivation in Goa and coastal Karnataka, focusing on farm-level losses, considering both present-year yield losses and replacement costs given the perennial nature of the vine. The findings reveal an average vine mortality rate of 9.64% due to foot rot, leading to an economic loss of USD 902.04/ha, equivalent to 56% of annual net returns. Using a dummy variable regression model, the effectiveness of various management practices employed by farmers in mitigating foot rot disease was assessed. The study shows that adopting management practices, such as avoiding water stagnation and ensuring good drainage, reduced losses caused by foot rot by 24% (USD 439/ha), while the use of fungicides led to a 20% reduction (USD 364/ha and in the absence of foot rot management strategies, the loss amounted to USD 1838/ha. In conclusion, educating farmers and promoting the adoption of integrated disease management practices can reduce foot rot losses, thereby enabling sustainable production and improved income from black pepper.

Keywords

Dummy variable regression model; economic impact; integrated disease management; *Phytophthora capsici*; western ghat

Introduction

Black pepper (*Piper nigrum* L.) is the most widely consumed spice globally, popularly known as "Black Gold" or the "King of Spices" (1, 2). Originating in the humid and tropical evergreen forests of the Western Ghats of India, it has spread to more than 25 countries including Vietnam, Brazil, Indonesia, Sri Lanka, China, Malaysia, etc. Indian black pepper, with its rich heritage in the spice trade, is renowned in the global market (3). Until 1999, India was the leading pepper producer; currently, Vietnam holds the top position, accounting for 30.10% of global production (2023). India ranked second in black pepper cultivation area (0.13 million hectares, 18.90% of the global share) and fifth in both production (65,740 tonnes, 7.69%) and exports (USD 79.23 million, 4.44%) during 2023. In the case of ground pepper exports, India ranked second (USD 43.49 million, 8.61% share) while Vietnam was the leading country (4). Geographically, the Western Ghat region of India is the primary centre of black pepper cultivation (5, 6). This region spans along the west coast of Kerala, Karnataka, Goa and Maharashtra states. Here, traditionally black pepper is grown as intercrop in plantation-based (areca nut and coconut) cropping systems (7, 8). In India, Karnataka is the leading state in both area (0.18 million hectares, 65% of national share) and production (36 thousand tonnes, 56%).

The foot rot disease, also called "quick wilt", which is caused by the soil-borne fungus *Phytophthora capsici,* is the most devastating disease in black pepper (9). The Western Ghat regions are considered as the hot spots for the foot rot of black pepper. Many black pepper plantations in the Western Ghat regions were wiped out due to this disease. This disease was one of the major reasons for India losing its age-old monopoly in the production and exports of black pepper (9). Further, many of the traditional cultivars in Kerala and Karnataka were becoming extinct by this disease infestation (2). Many farmers on the West Coast started giving secondary importance to black pepper as compared to plantation crops and were not following the cultural practices necessary for black pepper cultivation (10). The disease causes heavy losses to farmers as vines of all stages are susceptible, no cultivated variety is completely resistant and infection often leads to the mortality of perennial vines (11). The beginning of the southwest monsoon brings a wet and cloudy atmosphere to the west coast, which is congenial for the onset and spread of this disease. Moreover, this period coincides with the peak vegetative growth phase of the vine, characterized by the prevalence of the most susceptible tissues, thus increasing their vulnerability to infection (10). If the infection is aerial, leaves develop dark spots and defoliate, which then advances to the stem and causes the vine to wilt. If the root is infected, it rots and when the infection reaches the collar region, the vine collapses, hence the name foot rot or quick wilt. The disease spreads in a centrifugal pattern from the source of inoculum and previously affected vines are foci of secondary spread (9). The pathogen can spread through various means like rain splashes, windblown droplets, wounds, insects, irrigation water, live plants and soil. It can infect multiple susceptible hosts and can also survive in the soil for a prolonged period to re-emerge under favourable conditions, hence managing this disease is difficult (9, 10). Considering all these factors and the difficulty in controlling this disease solely through fungicides, integrated management approaches combining phytosanitation, cultural practices, chemical control techniques and the use of bio-control agents such as *Trichoderma* are recommended for effective management (10-13). However, the adoption of integrated disease management techniques by farmers varied due to several constraints (10).

Despite the widespread economic impact of *Phytophthora* foot rot disease, most existing studies primarily focused on its biological and epidemiological aspects, often reporting losses in percentage terms without quantifying them in economic values (14). It was reported that this disease caused up to 30% yield loss in India, 5-10 per cent in Malaysia and 30-40% in Indonesia (15-17). In Vietnam, despite the use of chemical fungicides, over 10,000 hectares of black pepper crop was infected and lost (10% of the national area) in 2016 (18). The objective of the present study was to estimate crop loss both in percentage and monetary terms using data from farmers' fields. As black pepper is a perennial vine, both present-year yield losses and replacement costs were considered while assessing monetary losses. Further, the study assessed the impact of each management practice adopted by farmers in reducing the economic losses caused by this disease, with the hypothesis that these measures significantly reduce economic losses.

Materials and Methods

Sources of data

The coastal parts of Karnataka and Goa fall under the West Coast Plains and Ghats Region. This region receives heavy rainfall (3,300 mm) with 90% of the annual rainfall occurring during southwest monsoon season (June to September) (19). The region is known for plantation crops and spices. The soils of this region are lateritic and moderately acidic (20). For collecting data from farmers, multistage stratified random sampling was adopted. From Goa, South Goa district and from Coastal Karnataka, Uttara Kannada district were randomly selected. From the selected districts, three talukas were randomly chosen: Ponda, Quepem and Canacona from South Goa; and Kumta, Honnavar and Ankola from Uttara Kannada. In each of these talukas, 15 farmers cultivating black pepper were randomly selected (Fig. 1). Data was collected using a pretested structured schedule during the 2023-24 period (Supplementary Table S1, Fig. S2). Surveys and interviews were conducted to gather data on various aspects of black pepper cultivation, including the incidence of foot rot, crop losses, replacement costs and management practices adopted by the farmers for managing the foot rot disease.

Weather parameters of the study area

To understand the weather patterns in the study area during 2023, monthly mean weather variables were computed using the NASA POWER database (21). The monsoon period (June to September) registered higher average daily rainfall, peaking in July at 40.95 mm/day (Fig. 2). From July to September, the average daily temperatures ranged between 25 and 26°C. Surface soil wetness was also higher during these months, its index reaching a maximum of 0.95 in July, as was the relative humidity, which was highest in July at 92.93%.

Estimation of losses due to foot rot disease

The study employed the methodology developed by the Food and Agriculture Organization of the United Nations (FAO) for assessing the impact of disasters on the agricultural sector (22). As indicated in Eqn 1, this methodology was adapted to evaluate the overall impact of foot rot disease encompassing both loss (reduced production) and damage (destruction of vines).

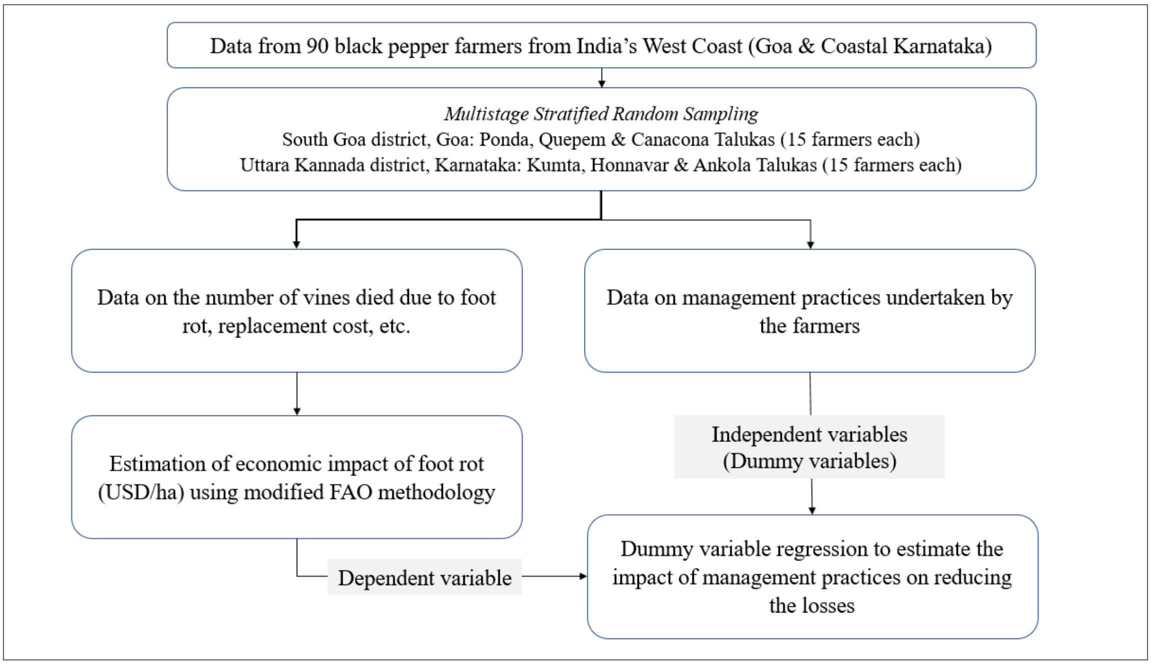

Fig. 1. Overview of the research methodology for estimating the economic impact of foot rot and assessing the impact of management practices on loss reduction in black pepper.

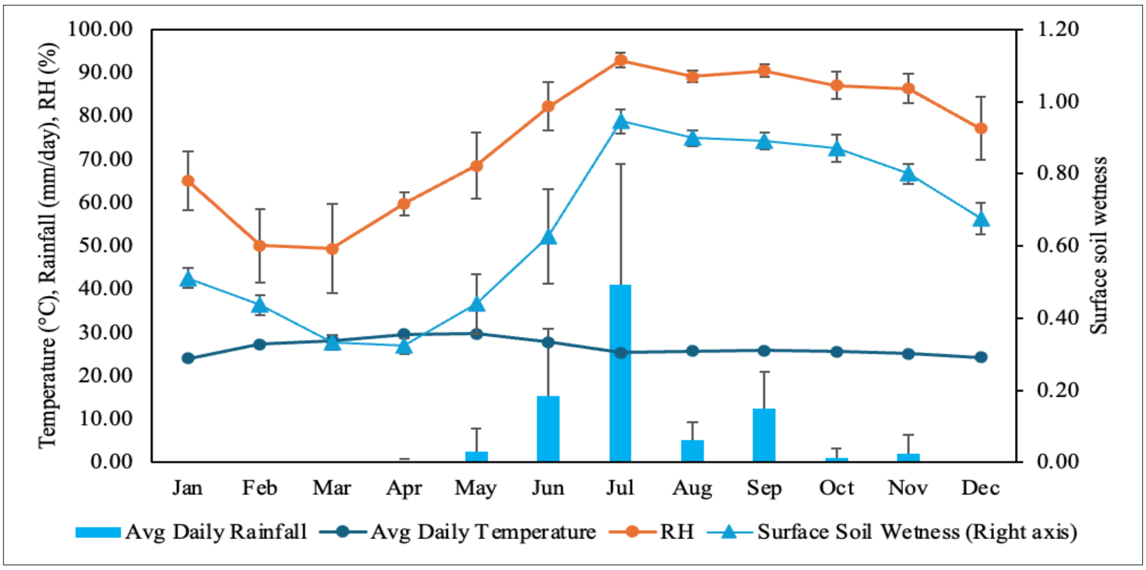

Fig. 2. Monthly mean weather variables of the study area during 2023: average daily rainfall, temperature, Relative Humidity and surface soil wetness. [Source: NASA (2024)]

Note: Error bars denote the standard deviation of the daily observed values

Total economic impact of foot rot disease on farm income =

Value of output lost in the present year due to death of vine + Replacement value of dead vines (Eqn. 1)

In Eqn 1, the value of output lost in the present year refers to the economic value of the black pepper produce lost due to the death of vines affected by foot rot disease. Replacement value of dead vines refers to the cost associated with replacing the vines destroyed by foot rot disease until vines become fully productive again. By summing up these two components, the total economic impact of foot rot disease on farm income was assessed.

Statistical analysis

To assess the effect of management practices in reducing the total economic impact of foot rot disease in black pepper production, a dummy variable linear regression model was employed. The total economic impact of foot rot disease (USD/ha) was used as the dependent variable in the regression model. The independent variables consisted of management practices recommended by the ICAR-Indian Institute of Spices Research, Kozhikode, Kerala, India, which were commonly adopted by farmers in the region (10, 12).

These practices were represented as binary dummy variables (D1 to D6) in Equation (2), each indicating whether a specific practice was implemented. The use of binary dummy variables ensures simplicity and effectively captures the contributions of these strategies as implemented in farmers' fields. This approach provides clear, actionable insights into the impact of individual practices despite variability across real-world conditions. While this method simplifies the representation of practices, it maintains interpretability and serves as a foundation for future research to explore variations in implementation intensity or quality.

$$y = \beta_0 + \beta_1 D_1 + \beta_2 D_2 + \beta_3 D_3 + \beta_4 D_4 + \beta_5 D_5 + \beta_6 D_6 + \epsilon \quad \text{(Eqn. 2)}$$

y = total economic impact of foot rot disease (USD/ha)

$$D_1 = \begin{cases} 1, & \text{if farmer aviods water stagnation and provides good drainage} \\ 0, & \text{otherwise} \end{cases}$$

$$D_2 = \begin{cases} 1, & \text{if farmer collects and burns diseased vine} \\ 0, & \text{otherwise} \end{cases}$$

$$D_3 = \begin{cases} 1, & \text{if farmer does not disturb the basins (digging)} \\ 0, & \text{otherwise} \end{cases}$$

$$D_4 = \begin{cases} 1, & \text{if farmer undertakes basal pruning} \\ 0, & \text{otherwise} \end{cases}$$

$$D_5 = \begin{cases} 1, & \text{if chemical fungicide is used} \\ 0, & \text{otherwise} \end{cases}$$

$$D_6 = \begin{cases} 1, & \text{if soiled runner shoots are avoided as plant materials} \\ 0, & \text{otherwise} \end{cases}$$

β_0 is the intercept representing the economic impact of the disease (USD/ha) when none of the above-mentioned management practices are followed. Each coefficient β_1 to β_6 quantifies the effect of the corresponding management practice on reducing the economic impact of the disease. To avoid the dummy variable trap, the redundant k^{th} dummy variables were not included and only k-1 dummy variables (2-1=1 in this study) were included. Multicollinearity, dependence among predictors in a regression model, poses a potential problem in all regression analyses and this can be diagnosed using measures such as Variance Inflation Factor (VIF) and tolerance (23). Using NumXL and R statistical software, analysis was carried out. The local currency, Indian Rupees (INR), was converted to US Dollars (USD) using the average exchange rate of 82.6 INR per 1 USD, calculated from the daily exchange rates throughout 2023. Fig. 1 illustrates the research methodology followed in this study, outlining the key steps involved, including sampling and the estimation of the economic impact of foot rot (the dependent variable) and the independent variables considered in the dummy variable regression model.

Results and Discussion

Summary statistics

Summary statistics covering demographic characteristics, management practices, black pepper yield and returns from the sample farmers were presented in Table 1. Results reveal that most of the respondents had a graduate level of education (37 farmers, 41.11%), followed by education up to 10^{th} standard (30, 33.33%). On average, the respondents had 15.98 years of farming experience. The average size of landholding was 1.40 hectares and the area under black pepper cultivation was 0.50 hectares. The share of black pepper area to the total landholding size averaged at 36%.

Table 1. Summary statistics of sample farmers cultivating black pepper in the study area (n=90)

Category	Metric	Details
	Demographics	
Education level	Up to 10^{th} Standard	30 (33.33%)
	10^{th}–12^{th} Standard	17 (18.89%)
	Graduate	37 (41.11%)
	Post-graduate	6 (6.67%)
Average farming experience	Years	15.98 ± 12.00
	Landholding and Crop Area	
Average landholding size	Hectares	1.40 ± 1.37
Average black pepper area	Hectares	0.50 ± 0.76
Average share of black pepper area	Percentage of total landholding	36%
	Cultivation Practices	
Black pepper standard	Areca nut	83 (92.22%)
	Coconut	75 (83.33%)
	Other Trees (e.g., mango, cashew)	55 (61.11%)
Average vines per farm	Count	209.12 ± 739.29
Vines per hectare	Count	370.33 ± 300.68
Black pepper varieties	Local Varieties/Others	85 (94.44%)
	Panniyur-1	75 (83.33%)
Major irrigation period		November–May
Irrigation source and type		Wells, Sprinkler Systems
	Challenges	
Peak vine death due to foot rot	Monsoon Period	71 (78.89%)
	Post-monsoon Period	19 (21.11%)
	Harvest and Economic Returns	
Number of pickings	Once	32 (35.56%)
	Twice	45 (50.00%)
	Thrice	13 (14.44%)
Average yield	kg/ha	256.93 ± 204.67
Average price received	USD/kg	6.63 ± 1.13
Cost of cultivation	USD/ha	407.57 ± 344.48
Gross returns	USD/ha	1664.31 ± 1300.72
Net returns	USD/ha	1256.74 ± 984.41

Note: Values are expressed as mean ± standard deviation where applicable. Percentages in parentheses indicate the proportionof respondents. For Black Pepper Varieties & Varieties percentages add up to more than 100% due to multiple options being possible.

Indian Rupees (INR) was converted to US Dollars (USD) using the average daily exchange rate of 82.6 INR per 1 USD for 2023.

Most respondents (92.22%) reported trailing black pepper vines on areca nut, followed by coconut (83.33%) and other standards such as mango, cashew nut and other trees (61.11%). Local varieties of black pepper were grown by the majority of the farmers (94.44%) followed by Panniyur-1 (83.33%). Earlier studies also revealed that Pannniyur-1 was the most popular variety in the west coast region and compared to other varieties, the net return from this variety was higher (24). During the post-monsoon season, farmers irrigate the black pepper along with the plantation crops mainly from open wells using sprinkler systems from November to May or till the onset of monsoon. The majority of the farmers (78.89%) reported that maximum vine death due to foot rot occurred during the monsoon period. The monsoon period in the study area corresponded with lower average temperatures and higher levels of rainfall, relative humidity and soil surface wetness. The weather conditions during this period were characterized by higher soil moisture and relative humidity (>80%) and lower temperatures (22-29°C), which were favourable for the rapid multiplication of this pathogen (16). The total number of pickings varied among farmers and most farmers (50.00%) undertook two pickings, followed by one picking (35.56%) and three pickings (14.44%). On average, 256.93 kg/ha was the yield of black pepper. The average price received was USD 6.63/kg and the average net return from black pepper was USD 1256.74/ha. Along with the problem of foot rot, farmers encountered stagnant market prices for black pepper, with real prices remaining at the same level observed a decade ago (Supplementary Fig. S2). It was reported that increased supply in the market and cheaper and illegal imports led to decreased domestic prices of black pepper in India. This resulted in a significantly reduced benefit-cost ratio (BCR), which declined from 2.45 BCR in 2015 to 1.34 BCR in 2019, not accounting for increased wages (25).

Distribution of important economic variables

Histograms depicting the distribution of key economic variables and foot rot damages in black pepper cultivation are shown in Fig. 3. Histogram reveals that the number of vines per hectare ranged from 8 to 1236, with a mean of 370 and a median of 305 vines/ha (Fig. 3 (a)). In the case of annual net returns obtained from black pepper, the mean was USD 1256.74/ha and the median was USD 1103.28/ha (Fig. 3 (b)). The percentage of vines that died due to foot rot ranged from 1% to 25%, with a mean of 9.64% and both the median and mode at 10% per year (Fig. 3 (c)). The annual economic impact of foot rot was estimated and it ranged from USD 33.42/ha to USD 2,972.74/ha (Fig. 3 (d)). The mean annual economic impact was USD 902.04/ha, with a median of USD 707.13/ha and a mode of USD 696.57/ha. On average, the annual economic impact of this disease was 56.27% of the annual net returns obtained from black pepper. Such substantial loss is the key factor in the marginalization of the black pepper area. In Vietnam, this disease is leading to a reduction of about a two per cent black pepper area every year (18).

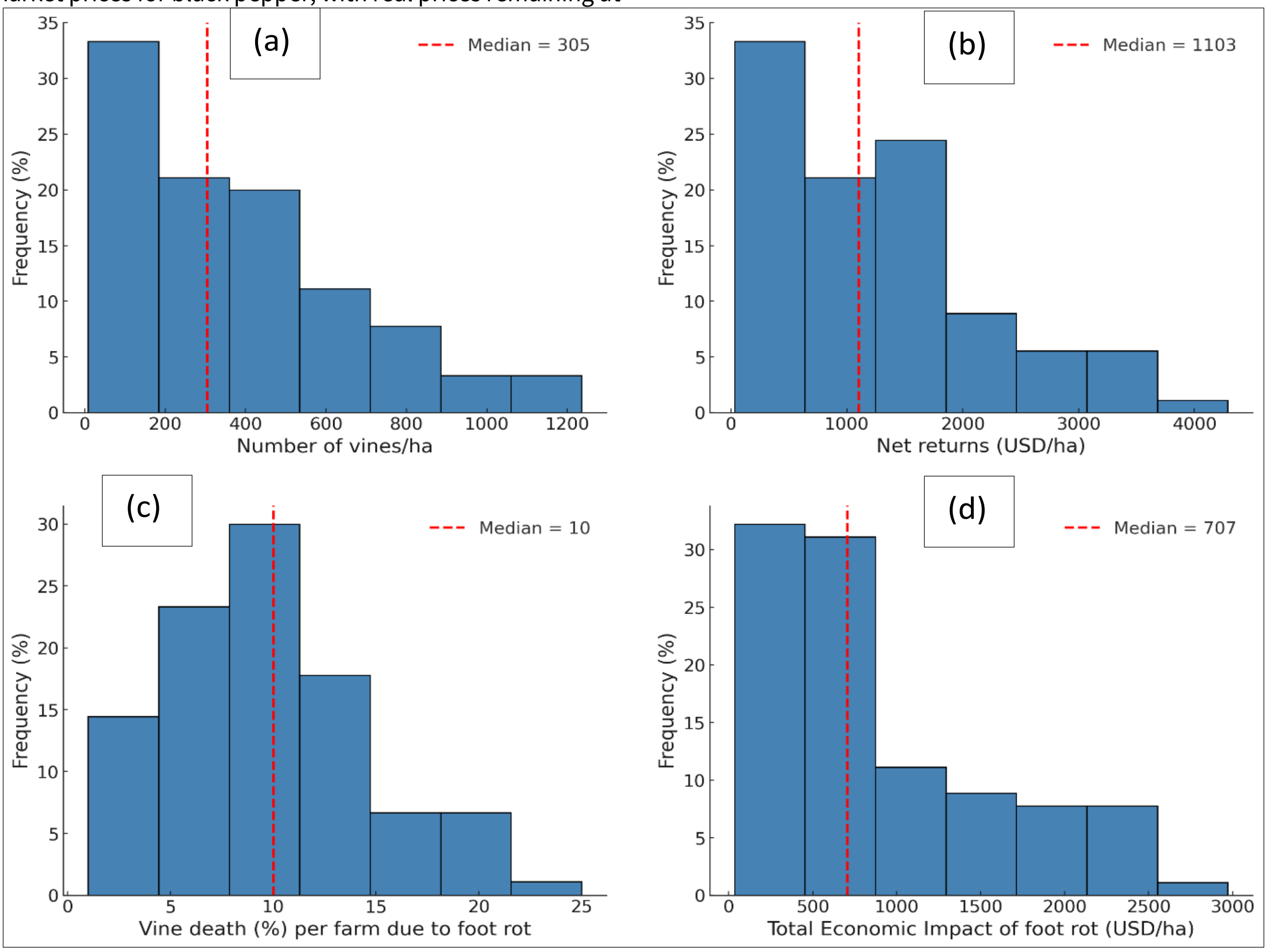

Fig. 3. Histograms of economic variables and foot rot damages in black pepper cultivation during the study period (2023-24): (a) Number of vines/ha (b) Net returns (USD/ha) (c) Vine death (%) per farm due to foot rot (d) Total economic impact of foot rot (USD/ha).

Box plot of economic impact by foot rot management practices

The box plots (Fig. 4) depict the economic impact of foot rot disease in black pepper across various management practices, comparing scenarios where the practices were followed versus not followed. The median economic impact showed reductions when practices were adopted. For example, avoiding water stagnation and ensuring good drainage reduced the median impact by approximately 80% compared to instances where this practice was not undertaken (Fig. 4 (a)). Similarly, the use of chemical fungicides led to a decrease of 75 per cent in the median economic losses as compared to the cases where it was not followed (Fig. 4 (e)). Practices such as collecting and burning diseased vines and avoiding soiled runner shoots as plant material also exhibited reductions in the economic impact (Fig. 4 (b) & (f)). The pathogen *Phytophthora capsici* is a polycyclic oomycete, known for its resilience and adaptability, making disease management difficult due to several critical factors. These include its multiple modes of transmission, ability to survive for prolonged periods without a host, presence of alternative host plants and the absence of commercially acceptable tolerant varieties adds further complexity to managing this disease (9, 13).

Impact of management practices: dummy variable regression

To assess the impact of commonly adopted management practices on reducing the economic impact of foot rot disease in black pepper, we used a dummy variable regression model. The results are presented in Table 2. The F-value of 19.98 indicates that the overall regression model was statistically significant (R^2=0.59, p<0.001). Generally, any variance inflation factor (VIF) that exceeds 10 and a tolerance value lower than 0.10 indicates a potential problem of multicollinearity (23). In this case, for all the independent variables, VIF and tolerance values were within these cutoff thresholds, indicating that multicollinearity levels were within acceptable limits.

The intercept of the regression model was USD 1,837.82/ha (90% Confidence Interval: 1,549.89, 2,125.76) and was statistically significant (p<0.001), representing the economic impact of foot rot disease on farm income in the absence of any foot rot management practices (baseline value). Given the average net return from black pepper at USD 1,256.74/ha, this annual impact is 46% higher than net returns, emphasizing the necessity of effective management practices to ensure economic viability.

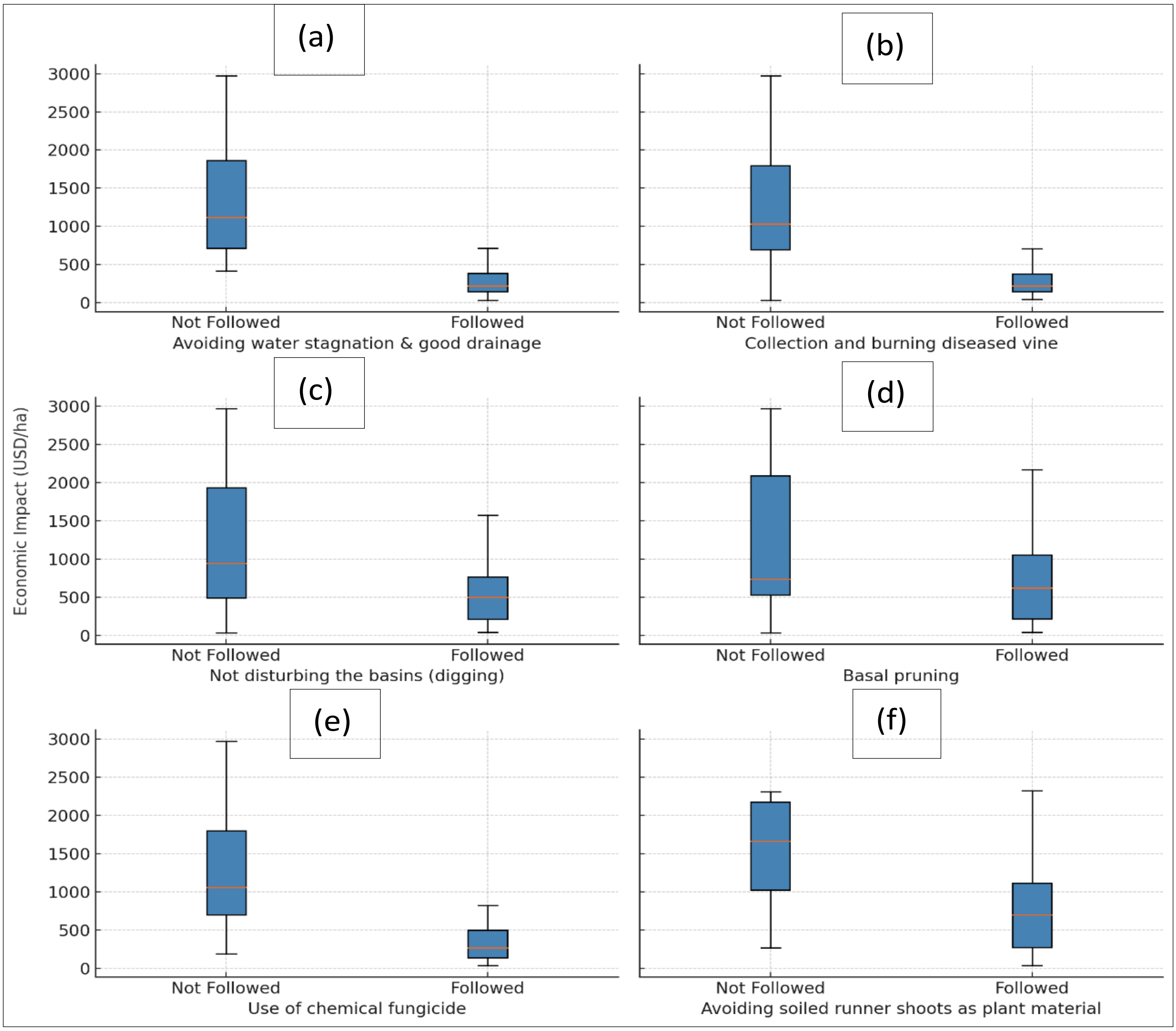

Fig. 4. Box plots of economic impact by management practices for foot rot disease in black pepper: (a) avoiding water stagnation & good drainage (b) collection and burning diseased vine (c) not disturbing the basins (digging) (d) basal pruning (e) use of chemical fungicide (f) avoiding sоiled runner shoots as planting material.

Table 2. Regression coefficients and costs of management practices for reducing economic impact of *Phytophthora* foot rot in farmers' fields (n=90)

Particulars	Coefficients	Lower bound	Upper bound	Standard Error	t Stat	P-value	Tol.	VIF	Cost (USD/ha)
Intercept	1837.82**	1549.89	2125.76	173.10	10.62	<0.001	-	-	
Avoiding water stagnation & good drainage	-438.94**	-696.63	-181.25	154.92	-2.83	0.006	0.46	2.19	52.76
Collection and burning of diseased vines	-281.87*	-533.81	-29.93	151.46	-1.86	0.066	0.50	2.02	14.22
Not disturbing the basins (digging)	-213.23*	-397.27	-29.19	110.64	-1.93	0.057	0.86	1.16	42.76
Basal pruning	-210.21*	-393.82	-26.60	110.38	-1.90	0.060	0.90	1.11	31.34
Use of chemical fungicides	-364.35**	-577.42	-151.29	128.09	-2.84	0.006	0.69	1.44	63.61
Avoiding soiled runner shoots as plant material	-346.77*	-637.57	-55.97	174.82	-1.98	0.051	0.95	1.05	15.07

Note**: R Square** = 0.59, **Adjusted R Square**= 0.56, **F value** = 19.98 (p<0.001)

** and * denote significance at 1% and 10% levels respectively

Upper and lower bounds represent the 90% confidence intervals for the regression coefficients

The coefficient for the management practice for avoiding water stagnation through good drainage indicates that undertaking this practice resulted in a reduction of losses due to foot rot by USD 438.94/ha (90% CI: -696.63, -181.25; t-stat -2.83, p< 0.006), while the cost of implementing this practice was USD 52.76/ha. This reduction equates to a 23.88% decrease in losses compared to the baseline value, highlighting the significant benefit of good drainage in mitigating the economic impact of the disease. As *Phytophthora* is a wet-weather pathogen, the rainy season (June-September) on the west coast provides congenial conditions for this soilborne disease to emerge and spread (10). Stagnant water creates anaerobic conditions that trigger germination of pathogen propagules and reduce production of phenol oxidase, phytoalexin, fixed nitrogen, while also suppressing mycorrhizal activity - factors which collectively increase host plant susceptibility (9). Hence, avoiding water stagnation and maintaining good drainage are the critical measures for the successful management of foot rot disease.

Further, the results indicated that the use of chemical fungicides (Bordeaux mixture/copper oxychloride) led to a reduction in losses by USD 364.35/ha (90% CI: -577.42, -151.29; t-stat -2.84, p= 0.006) which amounted to a 19.83% reduction as compared to the base value, with the cost of implementing this practice being USD 63.61/ha. Copper fungicides (Bordeaux mixture and copper oxychloride) were found highly effective in reducing this disease because of their toxicity and were popular in commercial plantations (11). The recommended practices include: (i) drenching vines within a 50 cm radius with copper oxychloride after initial monsoon showers (May-June), (ii) applying a foliar spray of Bordeaux mixture (1%), (iii) repeating drenching and foliar spray in August-September and (iv) if necessary, applying another round in October for prolonged monsoon (12). With the majority of the farmers cultivating the black pepper as an intercrop under areca nut gardens in the study area, while undertaking prophylactic sprayings of Bordeaux mixture to control fruit rot (*koleroga*) during monsoon season, aerial spraying on black pepper was also carried out (26). It was reported that farmers in Southern India managed *Phytophthora* mainly through the use of only copper fungicides as an aerial spray and were able to reduce losses substantially (27).

The results showed that avoiding soiled runner shoots as plant material reduced the losses by USD 346.77/ha (90% CI: -637.57, -55.97; t-stat -1.98, p= 0.051). Refraining from disturbing the basins decreased losses by USD 213.23/ha (90% CI: -397.27, -29.19; t = -1.93, p = 0.057) and basal pruning reduced losses by USD 210.21/ha (90% CI: -393.82, -26.60; t = -1.90, p = 0.060). Given the persistent presence of the pathogen in the farms, it is recommended to avoid root injury from cultural practices like digging, as any damage to the vine makes it more susceptible to infection. Since contaminated soil is the primary source of initial infection, foliage can become infected when soil splashes onto tender shoots trailing on the ground. Therefore, fresh runner shoots should be tied back to the standard or pruned to prevent them from trailing on the ground (12, 28).

The practice of collection and burning of diseased vines resulted in a reduction of losses by USD 281.87/ha (90% CI: -533.81, -29.93; t-stat -1.86, p= 0.066). Removal and destruction of dead vines along with roots are essential to reduce the build-up of inoculum in the soil as the pathogen can survive in the soil for up to 19 months in the absence of a host plant (12). The pattern of spread was non-random, with disease clusters forming around previously infected vines. Therefore, removing the inoculum source would reduce the inoculum load and retard the progression of the epidemic. Moreover, the pathogen can infect a wide range of plants, including solanaceous and cucurbitaceous species, as well as perennial crops like vanilla and cocoa which are generally grown in the areca nut and coconut plantations of this region, along with its relationship with microorganisms and parasitic nematodes (17). Therefore, reducing the pathogen load through the physical removal of dead vines aids in mitigating losses caused by this disease. Considering the importance of all these control measures, it is important to undertake the recommended package of practices for effectively managing this challenging disease. This study provides actionable economic insights into the devastating effects of foot rot disease, quantified at USD 1,838/ha, underscoring the critical need for effective management. The findings establish that simple interventions, such as improved drainage (reducing losses by 24%) and fungicide application (reducing losses by 20%), can substantially reduce the economic impact. Though the dummy regression approach captures the relationship in a simple and interpretable way, future research may capture variations in implementation intensity or quality of all management practices through the use of continuous variables.

Conclusion

The current study assesses the impact of foot rot disease on black pepper in the west coast region of India, quantifying the losses both in terms of vine mortality (9.64%) and monetary value (USD 902.04/ha) using a modified FAO methodology. The regression analysis estimates that, in the absence of disease management practices, foot rot disease causes an economic loss of USD 1838/ha in farm income. The use of chemical fungicides, management practices such as avoiding water stagnation and providing good drainage and the removal and destruction of dead vines result in a reduction of loss by USD 364/ha (20%), USD 439/ha (24%), USD 347/ha (19%), respectively. These findings highlight the potential for targeted interventions such as promoting integrated disease management, to enhance the resilience of black pepper production. Future studies could focus on longitudinal research with an expanded geographic scope to capture temporal dynamics and enhance the broader applicability of the findings. Further, continued research and extension efforts are required to develop innovative solutions, including the development of *Phytophthora* foot rot-tolerant varieties and to promote the widespread adoption of best management practices to ensure the long-term sustainability of black pepper production.

Acknowledgements

We would like to thank ICAR-Central Coastal Agricultural Research Institute, Goa and National Bank for Agriculture and Rural Development (NABARD) for providing research facilities and financial support. We would like to thank farmers who shared the data with us.

Authors' contributions

SB contributed to conceptualization, methodology, investigation and original draft preparation. VA contributed to methodology, writing-reviewing and editing. VP contributed to methodology, writing-reviewing and editing, visualization. NG handled the data curation and formal analysis.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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