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Effect of climate change on the incidence and severity of *Phytophthora* disease and evaluation of sustainable management strategies in vegetable production in Tanzania

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Abstract

Climate change is driving increased incidence and severity of *Phytophthora* diseases in Tanzanian vegetable production systems, threatening food security and smallholder livelihoods. Field assessments were conducted over four cropping seasons (2022–2024) across five major vegetable-producing regions (Arusha, Morogoro, Kilimanjaro, Iringa, and Tanga). Disease incidence and severity were recorded in tomatoes (*Solanum lycopersicum*), peppers (*Capsicum* spp.), and cucurbits, alongside climatic variables (temperature, rainfall, humidity), and evaluated under management strategies, including resistant varieties, nursery hygiene, raised beds with mulching, crop rotation, and integrated disease management. Regression analyses revealed that temperature ($p < 0.01$) and relative humidity ($p < 0.05$) significantly increased disease severity, while rainfall had no significant effect ($p > 0.05$). Management strategies significantly reduced disease severity ($p < 0.0001$), with integrated disease management outperforming standalone interventions. Resistant varieties reduced disease incidence by 40%, nursery hygiene by 30%, and crop rotation by 25%, while integrated strategies achieved the greatest overall efficacy. These results highlight the urgency of scaling climate-resilient integrated practices. We recommend targeted policy support, farmer training, promotion of resilient cultivars, and development of localized early warning systems to enhance adaptation and sustainability in climate-vulnerable vegetable farming systems in Sub-Saharan Africa.

Keywords *Phytophthora* species, Vegetable production, Climate-smart agriculture, Tanzania, Smallholder adaptation, GIS-based analysis

1 Introduction

Vegetable farming in Tanzania is a key source of income for rural households and a pillar of food security, nutrition, and employment [1]. Across highland and coastal regions, smallholder farmers cultivate a wide range of vegetables, including tomatoes, peppers, and cucurbits, which contribute significantly to local diets and regional markets [2].



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Growing demand for fresh produce has made vegetable production a vital driver of rural economic development, particularly empowering women and youth, who constitute the majority of the labor force in this sector [3].

However, vegetable production is increasingly threatened by plant diseases, with *Phytophthora* spp., particularly *Phytophthora capsici*, among the most devastating pathogens. These soil- and waterborne pathogens cause crown, root, and fruit rot in economically important crops such as tomato and pepper [4, 5]. Disease outbreaks are most frequent during the rainy season when high humidity and poorly drained soils create ideal conditions for infection. Once established, *Phytophthora* can spread rapidly, leading to significant yield losses and threatening farmer livelihoods [6].

Climate change exacerbates these challenges by altering plant-pathogen interactions. Over the past two decades, Tanzania has experienced shifting rainfall patterns, rising temperatures, and more frequent extreme weather events such as flash floods and prolonged dry spells [7]. These changes enhance pathogen aggressiveness, survival, and geographic spread. For example, intermittent heavy rains followed by high temperatures increase plant stress and facilitate the dispersal of infectious spores, creating conditions conducive to disease escalation [8, 9].

Smallholder vegetable farmers are highly vulnerable to *Phytophthora* outbreaks due to limited access to resistant varieties, inadequate drainage, poor nursery management, and insufficient extension support. Informal seed and seedling exchanges further facilitate pathogen spread [10]. Locally relevant, climate-resilient management strategies—including resistant cultivars, improved nursery hygiene, drainage, crop rotation, and integrated disease management—are therefore essential to enhance resilience and sustain vegetable production.

While global studies have shown that temperature, rainfall, and humidity influence *Phytophthora* outbreaks [11–15], evidence from Tanzania's diverse agro-ecological zones remains limited. This study investigates the impact of climate change on *Phytophthora* incidence and severity and evaluates the effectiveness of sustainable management strategies to inform climate-smart agricultural interventions.

2 Materials and methods

2.1 Study sites and farm selection

The study was conducted over four vegetable cropping seasons (2022–2024) across five major vegetable-producing regions in Tanzania: Arusha, Morogoro, Kilimanjaro, Iringa, and Tanga. These regions were selected based on their historical and current significance in horticultural production and their diverse agro-climatic conditions.

In each region, a combination of purposive and stratified random sampling was used to select representative vegetable farms cultivating tomatoes (*Solanum lycopersicum*) and peppers (*Capsicum* spp.), which are highly susceptible to *Phytophthora capsici* [16–18]. A total of 10 farms per region were included, giving 50 farms across all regions. Key farm characteristics, including size, irrigation method, and cropping practices, are summarized in Table 1.

2.2 Experimental design

On-farm and controlled field experiments were established to evaluate the effectiveness of climate-resilient *Phytophthora* management strategies. A randomized complete

Table 1 Farm characteristics across five major vegetable-producing regions in Tanzania

Region	Number of farms	Average farm size (ha)	Irrigation method	Cropping practices	Soil type	Fertilizer type	Plants ha ⁻¹
Arusha	10	1.2	Furrow	Crop rotation, raised beds, mulching	Sandy loam	Organic + NPK	30,000–35,000
Morogoro	10	1.5	Furrow/Rainfed	Intercropping, organic mulching	Loam	Organic + NPK	28,000–33,000
Kilimanjaro	10	1.0	Rainfed	Raised beds, crop rotation	Clay loam	NPK + Compost	32,000–36,000
Iringa	10	1.3	Furrow	Crop rotation, mulching	Sandy loam	NPK + Organic	29,000–34,000
Tanga	10	1.4	Furrow	Raised beds, intercropping	Loam-sand	Organic + NPK	30,000–35,000

block design (RCBD) with three replications per treatment was used to ensure statistical robustness and account for spatial variability (Table 2). Treatments included resistant varieties, nursery hygiene measures, raised beds with mulching, crop rotation with non-host legumes, and integrated disease management combining all strategies. Each block contained all treatments randomized. The same design was applied in each region for both on-farm and controlled experiments (Fig. 1).

2.2.1 Resistant varieties

Field experiments were conducted to evaluate the performance of *Phytophthora*-resistant and susceptible varieties of tomato and sweet pepper. The resistant cultivars included *Tomato cv. Tanya* sourced from the Tanzania Agricultural Seed Agency (ASA) and *Sweet Pepper cv. Yolo Wonder* from East African Seed Company, both selected for their documented tolerance to *Phytophthora* species [22]. Susceptible checks comprised commonly grown local cultivars, while untreated control plots consisted of susceptible cultivars managed under conventional farmer practices.

Each plot measured 3 m × 4 m, with a plant spacing of 0.6 m × 0.75 m to ensure uniform crop density and minimize edge effects. Irrigation regimes were adjusted to simulate contrasting moisture conditions of wet regime with irrigation events per week, 15 L m⁻² per event and dry regime with one irrigation event per week, 10 L m⁻² per event.

Disease development was monitored biweekly, and data were recorded on disease incidence, severity, and yield. Disease severity was visually assessed based on leaf wilting, stem lesions, and fruit rot symptoms. These evaluations enabled the assessment of varietal resistance and productivity under variable climatic and irrigation conditions.

2.2.2 Nursery management

Nursery trials evaluated pre-planting phytosanitary measures. Treatments included certified pathogen-free seed, sterilized media (steam-treated soil + compost), and clean irrigation water. Untreated control plots included non-certified seeds in unsterilized soil with regular water.

Seedlings were sown in raised beds (2 m × 1 m) arranged in RCBD with three replications. Environmental parameters (soil temperature, humidity, microbial load) were monitored weekly. Seedling growth and disease symptoms (damping-off, stem lesions, root rot) were recorded from emergence to transplanting [19].

Table 2 Comparison of management strategy on Phytophthora disease severity (%)

Variables	Sum of squares	Degrees of freedom	Mean squares	F-statistic	P-value	Coefficient of determination (R^2)	Adjusted R^2	95% confidence interval (%)
Management strategy	607.631	4	151.91	205.93	0.000	0.99	0.98	± 3.2
Region	0.192	2	0.096	0.13	0.880	—	—	± 0.9
Residual	5.901	8	0.738					
Total	613.72	14						

2.2.3 Cultural practices

Field trials were conducted over four vegetable cropping seasons (2022–2024) to assess agronomic practices to reduce *Phytophthora* inoculum and improve soil drainage. Interventions included raised beds, organic mulching, and crop rotation with non-host legumes. Untreated control plots consisted of conventional flat beds without mulch or rotation. Plots measured 3 m × 4 m, arranged in RCBD with three replications, standard plant spacing, and irrigation as described above. Planting dates avoided peak rainfall. Plots were monitored biweekly for disease incidence, severity, plant vigor, and yield. Soil moisture was measured using a portable soil moisture meter, and drainage assessed via water infiltration rates [20].

2.3 Data collection

Weather data, including daily temperature, rainfall, and relative humidity, were obtained from nearby meteorological stations managed by the Tanzania Meteorological Authority [21] for the period 2022–2024. These datasets were supplemented with on-farm environmental recordings, such as soil moisture (measured using Time Domain Reflectometry (TDR) sensors), soil temperature, and irrigation schedules, collected during the same period to monitor microclimatic conditions influencing disease development.

2.4 Disease assessment

Disease assessments were conducted on the selected plots using visual inspections of symptomatic plants. Disease severity was scored on a 0–5 scale (0 = no symptoms; 5 = complete collapse or extensive fruit/crown rot) every 14 days [22, 23].

2.5 Data analysis

Descriptive statistics (mean, standard deviation, and range) summarized climatic variables, seedling survival, disease severity, and crop yield. Disease counts were converted to percentage values using R software (Version 4.5.0). ANOVA evaluated the effects of management strategies on disease and yield, with significant differences ($p < 0.05$) separated using Tukey's HSD test.

Regression analyses quantified relationships between climatic factors (temperature, rainfall, relative humidity, and soil moisture) and disease severity, identifying key environmental drivers. Future risk was projected using IPCC Sixth Assessment Report scenarios (RCP 4.5 and 8.5) [24], and predictive models employing differential equations simulated disease dynamics under future climate conditions [25, 26].

Confidence intervals (95% CIs) were calculated for key effect sizes, and figures included error bars and regression bands to represent uncertainty. Analyses were performed in R (Version 4.2.2) and SPSS (Version 26), with geospatial mapping in QGIS (Version 3.28) and climate simulations using DSSAT and CSAT.

3 Results

3.1 Effect of climate change on *Phytophthora* disease

Over the past decade, *Phytophthora* incidence in vegetable production systems has increased, particularly in regions with erratic rainfall and persistent high humidity (Fig. 2). Rising average temperatures, especially above 25 °C, have accelerated disease

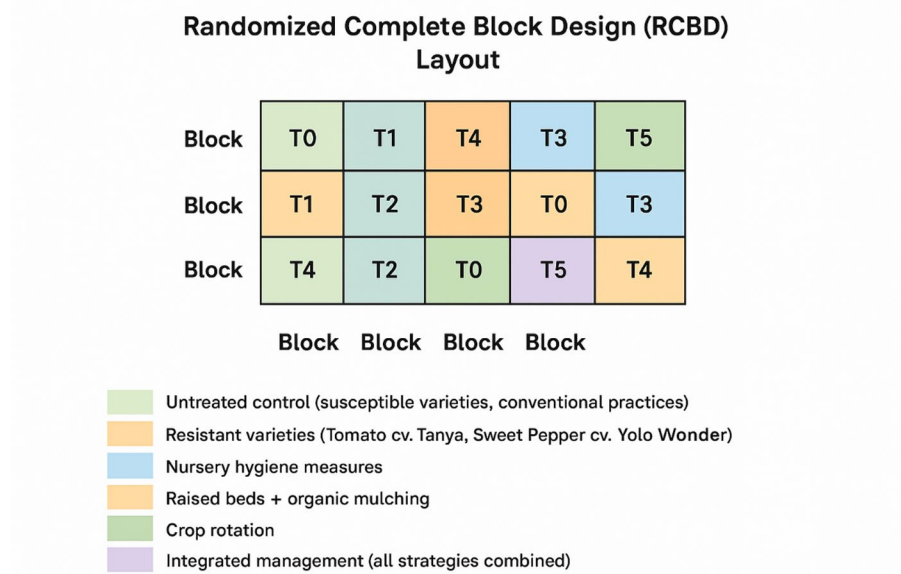


Fig. 1 Experimental design and treatments for Phytophthora management

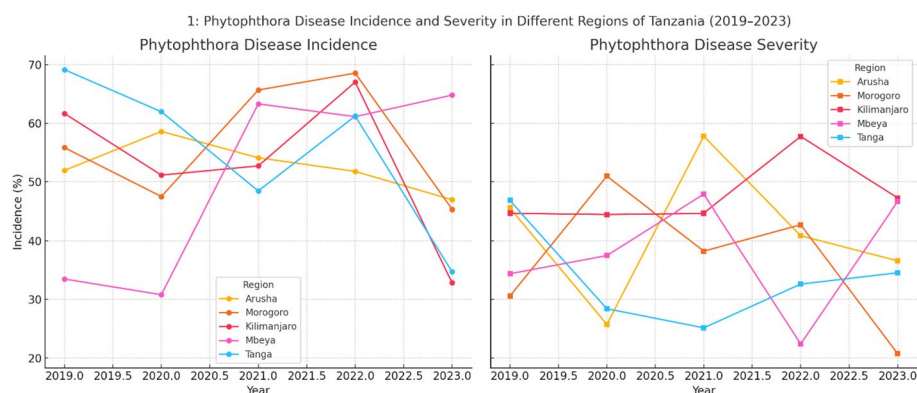


Fig. 2 Temporal trend in Phytophthora disease incidence and severity in different regions over the last 5 years in Tanzania

development and intensified crop losses, with key vegetable-producing areas such as Arusha, Morogoro, and Kilimanjaro being most affected.

Regression and correlation analyses confirmed that higher temperatures and extended wet periods were positively associated with disease severity, particularly in tomatoes and peppers, where waterborne sporangia further exacerbated pathogen spread (Fig. 3a). Regional patterns reveal that outbreaks intensify with increasing rainfall and moderate to warm temperatures, highlighting the strong climatic influence on disease dynamics.

3.2 Efficacy of integrated management strategies

Management strategies significantly influenced disease severity ($p < 0.05$), while regional differences were not statistically significant ($p > 0.05$; Table 2). All interventions reduced disease compared to the untreated control, with the most effective being resistant varieties, followed by nursery and cultural practices.

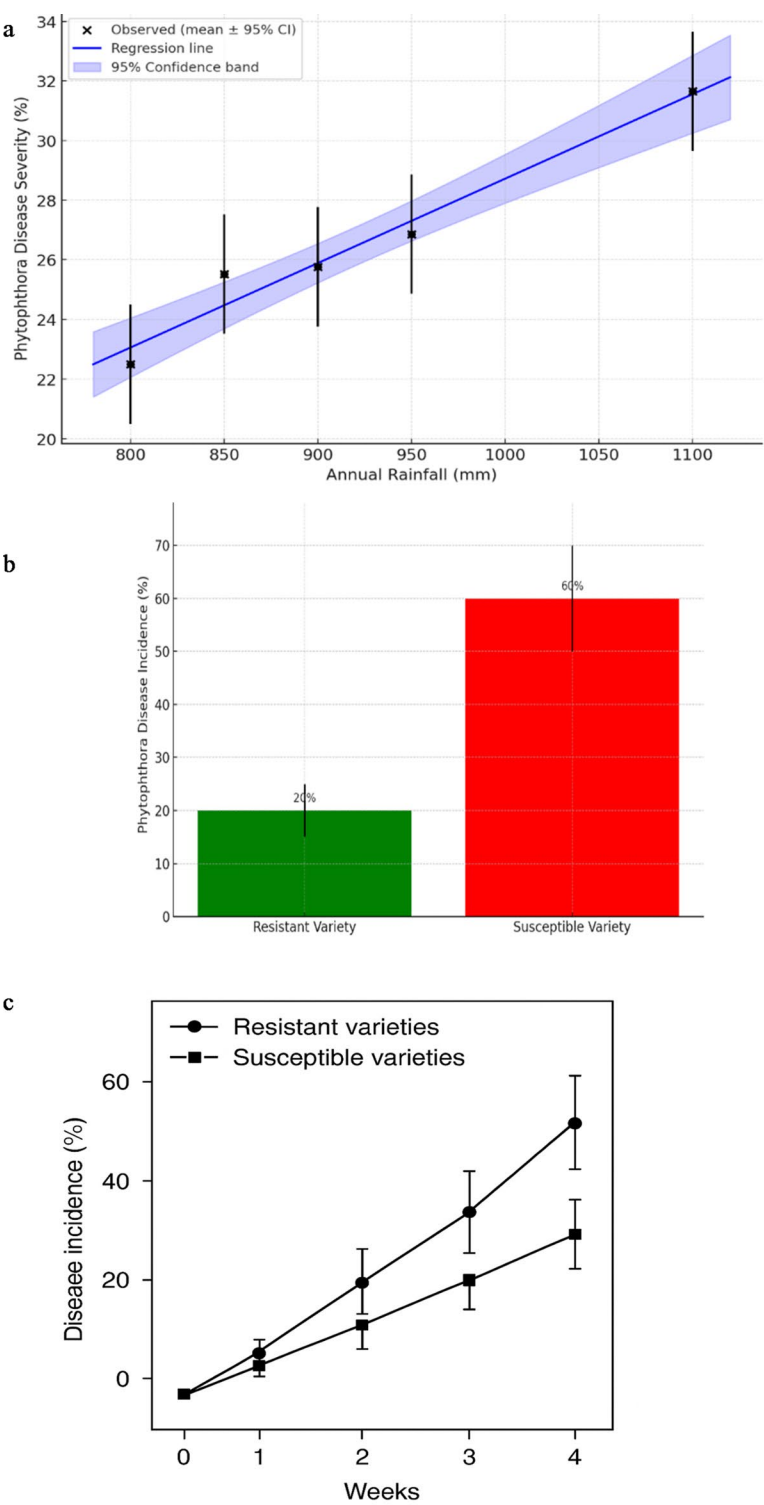


Fig. 3 **a** Relationship between rainfall and *Phytophthora* disease severity across regions in Tanzania (with 95% confidence band). **b** *Phytophthora* disease incidence (%) in resistant vs. susceptible varieties. **c** *Phytophthora* disease incidence in resistant versus susceptible varieties

Integrated Management: Across all regions, the combined application of resistant varieties, nursery, and cultural practices consistently outperformed single interventions in reducing disease severity and improving yield (Table 3).

Means followed by the same superscript letter within a column and region are not significantly different at $P < 0.05$ according to Tukey's Honest Significant Difference (HSD) test. Values are presented as mean $\pm$ 95% confidence interval. *Trichoderma* spp. = biological control treatment; "Integrated" = combined application of all management practices.

Resistant Varieties: Deployment of *Tomato cv. Tanya* and *Sweet Pepper cv. Yolo Wonder* reduced *Phytophthora* disease incidence by up to 40% compared to susceptible checks (Fig. 3b). Under periods of high temperature and humidity, these plants remained visibly healthier, showing reduced leaf wilting and fruit rot, indicating strong physiological resilience to climate-induced stress.

Regression plots including 95% confidence bands and error bars (Fig. 3c) further illustrate the relationships between climatic variables and disease severity, accounting for uncertainty in the estimates. These results suggest that deploying resistant varieties can effectively mitigate the adverse effects of variable weather on *Phytophthora* dynamics, supporting sustainable vegetable production under changing weather conditions.

Nursery Practices: Implementing pathogen-free seeds, sterilized media, and clean irrigation reduced disease incidence by approximately 30% (Fig. 4).

Cultural Practices: Raised beds combined with organic mulching minimized waterlogging, stabilized soil moisture, and reduced pathogen spread. Crop rotation with non-host crops further reduced disease by approximately 25% (Fig. 5).

Table 3 Effectiveness of management strategies against *Phytophthora* across regions in Tanzania

Region	Management strategy	Disease severity (%)	Yield increase (%)	Relative efficacy (%)
Arusha	Raised beds with mulching	27.8 $\pm$ 1.2 ^b	33.1 $\pm$ 2.0 ^{bc}	69.4 $\pm$ 2.1 ^c
	Crop rotation with non-host crops	32.5 $\pm$ 1.5 ^a	28.7 $\pm$ 1.8 ^c	63.3 $\pm$ 1.9 ^d
	<i>Trichoderma</i> spp. Application	25.1 $\pm$ 1.1 ^c	36.4 $\pm$ 2.1 ^b	74.2 $\pm$ 2.0 ^b
	Drip irrigation + fungicide schedule	20.6 $\pm$ 1.0 ^d	45.2 $\pm$ 2.2 ^a	82.6 $\pm$ 2.3 ^a
	Integrated	15.4 $\pm$ 0.9 ^e	59.0 $\pm$ 2.5 ^a	89.1 $\pm$ 2.4 ^a
Morogoro	Raised beds with mulching	28.9 $\pm$ 1.3 ^{bc}	31.8 $\pm$ 2.1 ^c	68.2 $\pm$ 2.2 ^c
	Crop rotation with non-host crops	33.8 $\pm$ 1.6 ^a	26.5 $\pm$ 1.7 ^c	61.5 $\pm$ 1.8 ^d
	<i>Trichoderma</i> spp. Application	24.2 $\pm$ 1.1 ^c	37.1 $\pm$ 2.0 ^b	75.5 $\pm$ 2.1 ^b
	Drip irrigation + fungicide schedule	21.8 $\pm$ 1.0 ^d	43.7 $\pm$ 2.2 ^a	80.9 $\pm$ 2.2 ^a
	Integrated	16.1 $\pm$ 0.9 ^e	57.4 $\pm$ 2.4 ^a	87.8 $\pm$ 2.3 ^a
Tanga	Raised beds with mulching	29.1 $\pm$ 1.3 ^{bc}	32.5 $\pm$ 2.0 ^c	68.1 $\pm$ 2.1 ^c
	Crop rotation with non-host crops	31.6 $\pm$ 1.4 ^{ab}	27.2 $\pm$ 1.8 ^c	62.8 $\pm$ 1.9 ^d
	<i>Trichoderma</i> spp. Application	24.0 $\pm$ 1.0 ^c	36.9 $\pm$ 2.1 ^b	73.7 $\pm$ 2.0 ^b
	Drip irrigation + fungicide schedule	19.5 $\pm$ 0.9 ^d	44.8 $\pm$ 2.3 ^a	81.7 $\pm$ 2.2 ^a
	Integrated	15.9 $\pm$ 0.9 ^e	58.2 $\pm$ 2.5 ^a	88.2 $\pm$ 2.4 ^a
Iringa	Raised beds with mulching	26.7 $\pm$ 1.2 ^{bc}	34.4 $\pm$ 2.0 ^b	70.3 $\pm$ 2.1 ^c
	Crop rotation with non-host crops	32.7 $\pm$ 1.5 ^a	29.3 $\pm$ 1.9 ^c	64.1 $\pm$ 2.0 ^c
	<i>Trichoderma</i> spp. Application	22.6 $\pm$ 1.0 ^{cd}	38.2 $\pm$ 2.1 ^b	76.4 $\pm$ 2.1 ^b
	Drip irrigation + fungicide schedule	18.9 $\pm$ 0.9 ^d	46.1 $\pm$ 2.3 ^a	83.2 $\pm$ 2.2 ^a
	Integrated	15.1 $\pm$ 0.8 ^e	59.8 $\pm$ 2.5 ^a	89.6 $\pm$ 2.4 ^a
Kilimanjaro	Raised beds with mulching	28.2 $\pm$ 1.2 ^{bc}	33.6 $\pm$ 2.0 ^{bc}	69.0 $\pm$ 2.1 ^c
	Crop rotation with non-host crops	33.1 $\pm$ 1.5 ^a	27.8 $\pm$ 1.8 ^c	62.7 $\pm$ 1.9 ^d
	<i>Trichoderma</i> spp. Application	23.9 $\pm$ 1.0 ^c	37.5 $\pm$ 2.1 ^b	74.9 $\pm$ 2.0 ^b
	Drip irrigation + fungicide schedule	20.3 $\pm$ 0.9 ^d	44.5 $\pm$ 2.3 ^a	82.0 $\pm$ 2.2 ^a
	Integrated	15.6 $\pm$ 0.9 ^e	58.5 $\pm$ 2.5 ^a	88.7 $\pm$ 2.4 ^a

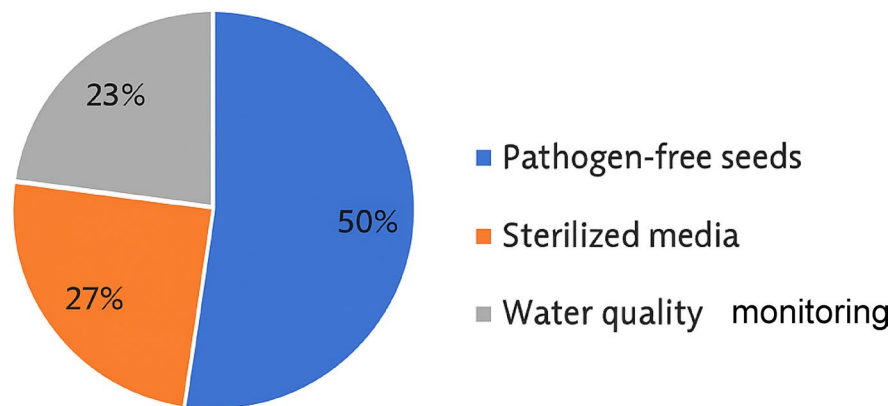


Fig. 4 Effect of sanitation and water quality management on *Phytophthora* disease incidence (%)

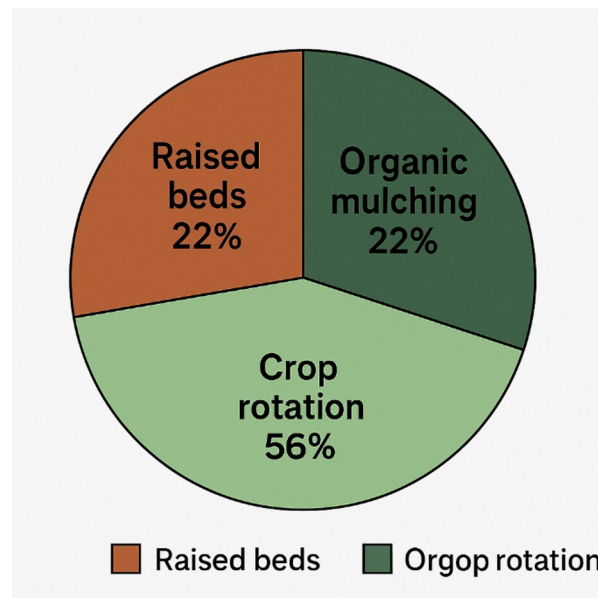


Fig. 5 Effect of raised beds, organic mulching, and crop rotation on *Phytophthora* disease incidence (%)

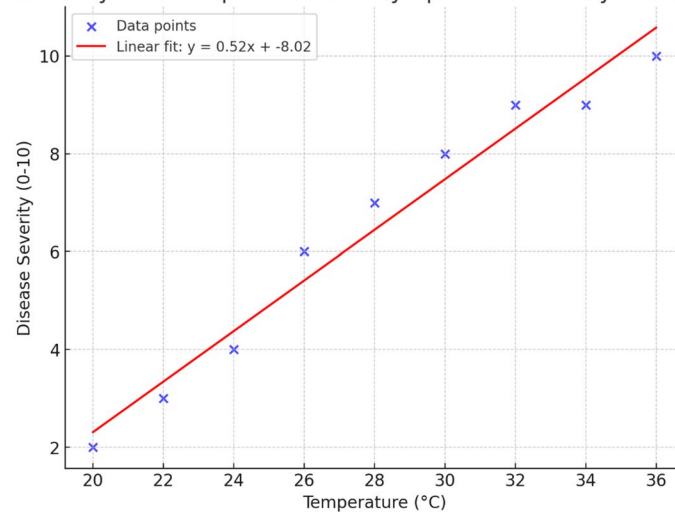
3.3 Effect of climate variables on disease severity

Regression analyses demonstrated that disease severity increased significantly with rising temperature during the wet season (slope = 1.24, $R^2 = 0.78$, $P < 0.01$; Fig. 6). High rainfall followed by elevated humidity further accelerated disease spread, confirming that climate is a key driver of *Phytophthora* dynamics.

4 Discussion

This study demonstrates that rising temperatures and increasingly erratic rainfall patterns are significantly favoring the proliferation of *Phytophthora* in vegetable production systems in Tanzania. Regression analysis revealed that disease severity increased for each degree rise in temperature during the wet season, and high rainfall combined with elevated humidity further accelerated disease spread. These results indicate that climatic stress not only creates favorable conditions for the pathogen but also increases crop

Regression Analysis of Temperature vs. Phytophthora Severity in Vegetable Crops

**Fig. 6** Regression of temperature against *Phytophthora* severity across different climatic zones in Tanzania

susceptibility through heat and waterlogging effects, consistent with previous reports [27, 28].

Among the interventions evaluated, resistant crop varieties had the greatest impact, reducing disease severity. Varieties such as *Tomato cv. Tanya* and *Sweet pepper cv. Yolo Wonder* maintained healthier foliage and lower fruit rot even under high temperature and humidity, demonstrating resilience under climate-induced stress. These findings underscore the importance of investing in breeding programs to develop crop varieties that can withstand both pathogen pressure and climatic variability, supporting earlier work [24, 29].

Nursery management practices also contributed substantially to disease reduction. Implementing pathogen-free seeds, sterilized media, and water quality monitoring led to a decrease in disease incidence. Among these measures, pathogen-free seeds had the largest effect, highlighting the role of seedborne inoculum as a primary source of early infections. The combined application of these sanitation measures demonstrates that a holistic approach to nursery management is essential for limiting early disease establishment, reducing reliance on chemical interventions, and enhancing resilience under variable climatic conditions [30, 31].

Field-level agronomic practices further mitigated disease impacts. Raised beds reduced waterlogging, a major risk factor for soilborne pathogens, while organic mulching stabilized soil moisture and temperature [32]. Together, these practices lowered disease incidence and improved overall crop vigor. Additionally, crop rotation with non-host species decreased pathogen buildup in the soil, providing a cost-effective and sustainable long-term management strategy [33].

Overall, integrating resistant varieties, nursery sanitation, and climate-smart field practices effectively reduces *Phytophthora* disease under variable climatic conditions [34]. Resistant varieties, reduced disease severity, nursery hygiene measures contributed a reduction, and field-level practices such as raised beds, organic mulching, and crop rotation further mitigated pathogen pressure [35]. By linking these outcomes to specific climatic stressors, high temperatures, erratic rainfall, and waterlogging, this study highlights practical, evidence-based strategies that farmers can adopt to build more resilient

vegetable production systems. Implementing these integrated approaches will limit disease outbreaks [36], enhance crop productivity, and provide a proactive framework for adapting vegetable farming to the challenges of climate change in Tanzania.

5 Conclusion and recommendations

Phytophthora diseases are a growing threat to vegetable production in Tanzania, increasingly exacerbated by rising temperatures, erratic rainfall, and prolonged humidity. Our results demonstrate that specific management interventions have measurable effects on disease suppression and crop resilience. Resistant crop varieties reduced disease severity, pathogen-free nursery systems decreased early infections, and field-level practices, including raised beds, organic mulching, and crop rotation, further limited soilborne pathogen buildup. Collectively, these strategies effectively reduce disease pressure and maintain vegetable productivity under variable climatic conditions.

To enhance these effects, targeted investments in breeding programs for pathogen- and climate-resilient varieties are essential. Promoting biosecure nursery practices and strengthening extension services to deliver location-specific guidance on integrated disease management will further improve outcomes. Together, these evidence-based interventions provide a practical framework for managing Phytophthora, supporting climate-resilient vegetable production, and sustaining productivity in Tanzanian farming systems.

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Author contributions

A.A.A. was responsible for the conceptualization, writing, and review of the manuscript.

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Data availability

The datasets generated and analyzed during this research be obtained from the corresponding author upon reasonable request, subject to confidentiality agreements.

Declarations

Ethics approval and consent to participate

This research involved observational research on smallholder vegetable farmers in Tanzania. Formal ethical approval was not required for this type of research. However, all procedures complied with institutional and national guidelines for research involving human participants. Informed consent was obtained from all participating farmers prior to data collection. Participants were informed about the purpose of the research and their voluntary involvement.

Consent for publication

All participants provided consent for the use and publication of anonymized data generated from this research.

Competing interests

The authors declare no competing interests.

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