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Influence of Farmers' Management Practices on the Prevalence and Spread of Potato Bacterial Wilt (Ralstonia solanacearum) in District Okara, Punjab, Pakistan

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ABSTRACT

Potato (*Solanum tuberosum* L.) is a vital food and cash crop in Pakistan, with Punjab accounting for over 75% of national production. District Okara is a major potato-growing region; however, bacterial wilt caused by *Ralstonia solanacearum* poses a serious threat, leading to yield losses of 30–80%. This study examined the influence of farmers' management practices on the prevalence and spread of bacterial wilt. Further, it measured the spatial distribution of potato bacterial wilt in the study area. A total of 225 farmers were surveyed using a structured questionnaire. Results revealed that 39.6% of farmers did not use certified seeds and relied on seed saved from previous crops, and 49.8% used flood irrigation; the practices favoured the spread of Ralstonia solanacearum. The overall disease prevalence was 60%, with the highest recorded in Village G (78.38%). Statistical analyses showed significant associations between disease incidence and farm practices, including seed source ($p = 0.001$), crop rotation ($p = 0.000$), irrigation method ($p = 0.002$), and field sanitation ($p = 0.000$). Access to extension services ($\chi^2 = 25.12$; $p = 0.000$) strongly influenced the adoption of recommended practices. These findings underscore the urgent need for integrated disease management strategies, farmer education, and improved access to certified seed to reduce disease spread and enhance sustainable potato production.

***Keywords*:** Potato production, *Ralstonia solanacearum*, Bacterial wilt, Disease prevalence, Management practices, Certified seed, Punjab, Pakistan, Integrated disease management

INTRODUCTION

Potato (*Solanum tuberosum* L.) is a critical staple food and a vital cash crop worldwide, providing significant food, nutrition, and income for millions of farmers and consumers. Pakistan ranks among the major potato-producing countries in South Asia, with Punjab accounting for over 75% of the national production due to its favorable agro-climatic conditions and fertile soils (Pakistan Bureau of Statistics, 2024). District Okara, located in central Punjab, is particularly renowned for commercial potato cultivation, playing a vital role in both domestic supply and exports. However, potato production in the region faces several biotic constraints, of which bacterial wilt caused by *Ralstonia solanacearum* is among the most devastating (Ali et al., 2023; Adnani et al., 2024). As per a large body of literature (Anoumaa et al. 2022; Akiko et al. 2019), a single type of soil-borne pathogen can cause widespread impoverishment and economic hardships, especially in communities that rely heavily on potatoes, leading to a decline in tuber quality.

The rapid transmission of bacterial wilt, through the use of contaminated farm iron, planting materials, soil, and irrigation water, has proven to be a daunting challenge for disease control (Assefa, 2020). In Punjab, the disease caused a major deficit in crop yields ranging from 30 to 80 percent, as a result of faulty cultivation practices (Atieno et al. 2023). The ability of Pseudomonas solanacearum to remain firm in soil and thrive under diverse environmental conditions makes it more challenging to control. The impact of farmer practices on the tuber, crop rotation, irrigation, disease control, and the use of resistant cultivars can influence the proliferation and control of bacterial wilt (Belay et al. 2022). Sadly, a significant number of resource-poor farmers located in Okara predominantly depend on traditional practices, causing the proliferation of bacterial wilt (Bereika et al. 2020)

Worldwide, research has indicated that implementing appropriate disease management practices, such as the use of disease-free seeds, appropriate crop rotations, equipment disinfection, and prompt regional rostering, can help

mitigate bacterial wilt (Buja et al. 2021, Devaux et al. 2021). Unfortunately, in many developing countries, failing to appreciate the problem, the disproportionate access to expansion services, and the socio-economic-environment milieu greatly hinder efficient disease management practice (Devaux et al. 2021). In Pakistan, research on the relationships between farmer practices and bacterial wilt circulation is limited, especially in major potato-producing areas such as Okara. Understanding these linkages is crucial for designing effective extension programs and policy interventions to curb the spread of the disease.

The purpose of this study is to assess the impact of farmers' management practices on the spread of potato bacterial wilt in the district of Okara, Punjab, Pakistan. In particular, the study is based on the following objectives: (1) Identification of current potato production and management practices after farmers, (2) Assess the spread and spatial distribution of bacterial wilt and (3) Analyze the relationship between specific agricultural practices and potato bacterial wilt.

MATERIALS AND METHODS

Research design

Data were collected in the 2024–2025 potato cropping season using a cross-sectional quantitative research design. The study integrated spatial mapping, farmer survey data, field disease assessments, and laboratory confirmation to understand the disease's dynamics.

Study population

Okara is one of Punjab's Districts most rich in potato cultivation, owing to its fertile soil and favorable climatic conditions, which make it ideal for farming. The district comprises five major tehsils: Okara, Dapalpur, and Renla Khurd. These tehsils also report the infamous bacterial wilt outbreak season. As of the year 2024, the total number of farmers in the district is approximately 4,500. This target population included small-, medium-, and large-scale potato farmers. Using a simple random sampling technique, one tehsil was selected, and 15 villages were randomly chosen from it. 15 farmers were randomly selected from each village, for a total sample of 225.

Data collection

Data collection was carried out in three integrated phases. In Phase 1, a structured questionnaire was used to gather information on farmers' production and management practices. The survey included sections on farmer demographics (age, education, farming experience, landholding size, and income sources), seed selection (certified, farm-saved, or uncertified seed), irrigation practices (flood, furrow, or drip irrigation), crop rotation strategies, field sanitation, use of resistant potato varieties, and access to extension services. The questionnaire was pre-tested on 20 farmers outside the study area to ensure clarity and validity. Data were collected through face-to-face interviews conducted in the local language (Punjabi) by trained enumerators.

In Phase 2, field surveys were conducted to assess bacterial wilt prevalence and its spatial distribution. For each farm, three representative plots measuring 10 m × 10 m were selected for plant observation. Disease incidence was recorded based on visual symptoms, including wilting, yellowing, and vascular discoloration, following the diagnostic guidelines of Elphinstone (2005). The Prevalence percentage was calculated using the following formula:

$$\text{Prevalence \%} = \frac{\textit{Number of infected fields}}{\textit{Total number of fields observed}} \text{ x } 100$$

The disease severity index was calculated by:

$$\text{DSI} = \frac{\sum (\text{n x v})}{N \, x \, V}$$

Where:

- n = Number of plants in each severity category
- v = Numerical value of each severity category (0–5 scale)
- N = Total number of plants observed
- V = Maximum numerical value of the severity scale

Data analysis

Data analysis was performed using SPSS v26. Descriptive statistics such as means, frequencies, and percentages were used to summarize farmer demographics, management practices, and disease prevalence. Inferential statistical tests were conducted to explore relationships between variables. A Chi-square (χ^2) test was applied to determine associations between categorical variables, such as education level and adoption of management practices. The general formula for the Chi-square test is:

$$X^2 = \sum \frac{(O-E)^2}{E}$$

Where:

O = observed frequency

E = expected frequency

An independent t-test/ANOVA was used to assess the relationship between different farm management practices and the prevalence of potato bacterial wilt **(***Ralstonia solanacearum***).**

Reliability and validity

To ensure reliability and validity, Cronbach's alpha was calculated for each questionnaire section, with all values exceeding 0.70, indicating good internal consistency. Triangulation was achieved by combining farmer self-reports, direct field observations, and laboratory confirmation of the pathogen.

Ethical considerations

Ethical views were addressed by obtaining formal approval from the Institutional Review Board of the Agricultural University. Farmers were informed of the study's purpose, and verbal consent was obtained before the interview. Participants were assured that their data would remain confidential and would be strictly used for educational and policy-making purposes.

RESULTS AND DISCUSSION

Demographic characteristics

Table 1: Demographic Characteristics of Respondents (n = 225)

Variable	Category	Frequency (f)	Percentage (%)
Age (years)	20 – 30	35	15.6
	31 – 40	64	28.4
	41 – 50	72	32.0
	Above 50	54	24.0
Education Level	No formal education	48	21.3
	Primary (1–5 years)	52	23.1
	Secondary (6–10 years)	64	28.4
	Higher secondary and above	61	27.1
Farm Size (acres)	< 5 acres (Small)	78	34.7
	5 – 10 acres (Medium)	94	41.8
	> 10 acres (Large)	53	23.5
Farming Experience	< 10 years	46	20.4
	10 – 20 years	83	36.9
	> 20 years	96	42.7
Household Size	1 – 5 members	67	29.8
	6 – 10 members	118	52.4
	> 10 members	40	17.8
Access to Extension Services	Yes	137	60.9
	No	88	39.1

The demographics of potato farmers in Okara District, Punjab province, Pakistan, are described in Table 1. The results show that the largest age cohorts are middle-aged, with 32% in the 41-50 year age group, and 28.4% in the 31-40 year age group. This indicates that middle-aged farmers primarily engage in potato farming. Similar conclusions have been reached by Ali et al. (2023) and Hussain et al. (2022), who stress that middle-aged farmers are more productive in potato farming and in potato disease management. Regarding education, 28.4% and 27.1% of the respondents reported completing secondary school and attaining the higher secondary school level, respectively, while 21.3% reported having no formal schooling. This scenario indicates that a significant number of farmers have low or basic educational qualifications. As noted by Parveen et al. (2022) and FAO (2022), farmers' educational level is critical in understanding and practicing new farming techniques, particularly in the integrated management of bacterial wilt in potato.

The survey data revealed that about 41.8% of respondents operated on medium-sized farms (5–10 acres), 34.7% on small farms (<5 acres), and 23.5% on large farms (>10 acres). This illustrates a mixed farming system in which both smallholder and semi-commercial farmers coexist. Farm size showed a similar pattern in Punjab (FAOSTAT et al. 2022; Wang et al. 2023), indicating that farm size determines resource allocation and the adoption of higher production technologies.

Experience in farming was also significant, with 42.7% of farmers having over 20 years of experience and 36.9% having from 10 to 20 years. These farmers are more likely to understand disease symptoms and control practices in comparison to the rest of the population. These findings are consistent with the studies by Yao et al. (2023) and Kapalasa et al. (2022), who argued that experience is crucial for the use of technology and for decisions made on the farm. Household size analysis revealed that 52.4% of households had 6 to 10 members, indicating a moderately large family size. Evidence suggests that the more family members there are, the more likely they are to contribute to farm work. This reduces the need for hired labor but increases the demand for change in the farm's income distribution (Hussain et al. 2022). 60.9% of farmers had access to extension services, while 39.1% did not. This is an indicator of

moderately low institutional support, which also suggests strong underperformance by the extension department in disseminating agricultural information. Extension services are fundamental for promoting knowledge and practice of integrated disease management, particularly for controlling bacterial wilt, as emphasized by Karacic et al. (2024) and Karlsson et al. (2020).

Potato Production and Management Practices

Table 2: Current Potato Production and Management Practices Followed by Farmers (n = 225)

Practice Area	Category/Option	Frequency	Percentage
Seed Source	Saved from previous harvest	89	39.6
	Purchased from local market	73	32.4
	Certified seed from government agencies	41	18.2
	Certified seed from private companies	22	9.8
Crop Rotation Practice	Regular rotation (2–3 years)	97	43.1
	Occasional rotation	65	28.9
	No rotation (continuous potato)	63	28.0
Irrigation Method	Flood irrigation	112	49.8
	Furrow irrigation	76	33.8
	Drip/Sprinkler irrigation	37	16.4
Fertilizer Application	Balanced use (NPK based on recommendation)	84	37.3
	Excessive nitrogen use	87	38.7
	Random/unplanned application	54	24.0
Field Sanitation	Regular cleaning of tools and equipment	62	27.6
	Occasional cleaning	77	34.2
	No cleaning	86	38.2
Use of Resistant Varieties	Yes	68	30.2
	No	157	69.8

The findings indicate that a significant proportion of farmers rely on saved seed from previous harvests (39.6%), while 32.4% purchase seeds from local markets**,** which may be of uncertain quality. Only 18.2% source certified seeds from government agencies**,** and a mere 9.8% source them from certified private companies. This reflects a low adoption rate of quality seed, which aligns with previous studies reporting that limited access to certified seeds and high costs often discourage farmers from using improved planting materials (Kinyua et al., 2022; Kithome et al., 2022). The predominance of uncertified seed sources contributes to the spread of diseases such as bacterial wilt by allowing pathogens to persist on infected tubers (Gobena, 2020). Regarding crop rotation practices**,** 43.1% of farmers follow regular rotation (2–3 years), which is beneficial for soil health and disease control. However, 28.9% practice occasional rotation**,** and 28.0% report no rotation at all**,** continuously cultivating potatoes in the same fields. Continuous monocropping has been widely recognized as a key factor that exacerbates the prevalence of soil-borne diseases like bacterial wilt (Korir et al., 2020). These findings highlight the need to promote crop rotation as a sustainable disease management strategy. In terms of irrigation practices**,** flood irrigation remains the most common method (49.8%), followed by furrow irrigation (33.8%), while only 16.4% of farmers have adopted drip or sprinkler systems**.** The reliance on flood irrigation not only leads to inefficient water use but also increases the risk of bacterial wilt spread through contaminated water channels (Hayes et al., 2022). Modern irrigation methods, such as drip irrigation, have been shown to reduce pathogen spread and enhance water-use efficiency, suggesting a critical area for intervention and farmer training (Izuogu et al., 2024).

Regarding fertilizer application, such as the practice referred to as "balanced fertilizer application based on recommendations," 37.3% applied fertilizers in a random or imbalanced way, 24.0% applied unbalanced fertilizers, while 38.7% reported unjustified application of excessive nitrogen. Njenga et al. (2021) even claim that excessive vegetative growth, coupled with nitrogen overuse, puts potato plants at a higher risk of contracting bacterial wilt and other infections. Soil balancing and nutrient management can stem from mere soil testing and can improve yield while reducing the incidence of disease.

Izuogu et al. (2024) further verified that bacterial wilt and other bacterial pathogens can be transmitted between fields due to inadequate sanitation. In the 2024 study, only 27.6% of farmers cleaned and sanitized their tools and equipment, while 34.2% did so only occasionally, and 38.2% claimed to never clean and sanitize their equipment. These results suggest there is little understanding of how integrated disease management can provide levers to negative citizen behavior. The only other explanation is poor awareness among farmers. This aligns with Gobena (2020), who noted that there is little support from information service providers to help farmers manage disease.

The access to and promotion of resistant varieties could be instrumental in reducing bacterial wilt prevalence. Evidence indicates that poorly designed management practices contribute to the enhanced spread and persistence of bacterial wilt. The results highlight the need for integrated disease management, including the promotion of certified seeds, strategic crop rotation, rational fertilization, careful weeding, and the planting of resistant varieties to lessen the disease's impact and promote more sustainable potato farming in the area.

Prevalence and Spatial Distribution of Bacterial Wilt

Insights into the prevalence and spatial distribution of potato bacterial wilt (Ralstonia solancearum) in the seven surveyed villages of District Okara, Punjab, Pakistan, are illustrated in Table 3. The results show that bacterial wilt disease is endemic and remains a potential and alarming threat to potato production in the region, with a startling 60% disease prevalence and a population-average Disease Severity Index (DSI) of 0.47.

Table 3: Prevalence and Spatial Distribution of Bacterial Wilt in Surveyed Villages (n = 225 fields)

Village/Area	Total Fields Surveyed (n)	Number of Infected Fields (n)	Prevalence (%)	Disease Severity Index (DSI)
Village A	30	18	60.00	0.45
Village B	28	13	46.43	0.38
Village C	32	15	46.88	0.40
Village D	25	17	68.00	0.52
Village E	35	20	57.14	0.47
Village F	38	23	60.53	0.49
Village G	37	29	78.38	0.58
Overall Total	225	135	60.00	0.47

The highest prevalence was observed in Village G at 78.38%, alongside the region's highest DSI (0.58), suggesting infection levels that could substantially reduce crop yield. In contrast, the lowest prevalence (46.43%) and DSI (0.38) were observed in Village B (South Okara), indicating comparatively superior disease control and management practices. Moderate prevalence levels were recorded in Village A (60.00%), Village F (60.53%), and Village E (57.14%). The difference in bacterial wilt prevalence was due to differences in farming practices, environmental factors, and available extension services. Increased disease prevalence was observed in villages without access to certified seeds, with poor crop rotation, and predominantly using flood irrigation. For example, Village G relied heavily on saved seed and continuous potato cultivation, which are recognized as major risk factors for disease persistence and spread (Njiru et al., 2021; NPCK, 2021). In addition, flood irrigation has the potential to enhance the spread of Ralstonia solanacearum, which sluggishly moves in saturated soils and can directly translocate between diseased fields (Izuogu et al., 2024).

The presence of disease hotspots in peripheral regions demonstrates the impact of socio-economic conditions and infrastructure on disease control. Farmers in these regions do not have access to timely training and extension services, which results in poor adoption of some of the most basic recommended practices, such as field sanitation, irrigation, use of resistant varieties, and proper irrigation (Ali et al., 2022). This corresponds to the findings of earlier studies on potato bacterial wilt in South Asia and Africa, where bacterial wilt has been reported as a major constraint to sustainable production (Khairy et al., 2021; Liu et al., 2022). This underscores the importance of providing education on seed systems, integrated disease management, and targeted interventions to constituents affected by potato bacterial wilt in District Okara.

Relationship between Farm Management Practices and Potato Bacterial Wilt Incidence

The relationship between farm management practices and potato bacterial wilt (Ralstonia solanacearum), as reported by some farmers in District Okara, Punjab, is captured in Table 4. The results suggest that seed source is important for disease prevalence. Farmers who used saved seed had the highest mean disease incidence (64.85%), while those who bought seed from the local market had slightly lower disease incidence (59.32%). However, those using certified seed from the Government (48.21%) or private companies (45.78%) recorded significantly lower levels of bacterial wilt ($p = 0.001$). This supports the findings of Kwambai et al. (2024), who indicated that certified seed is often the primary source of R. solanacearum and enables its introduction and spread of bacterial wilt. Disease incidence was also significantly associated with crop rotation. Farmers who practiced continuous cultivation of potato reported the highest incidence (67.50%) while those who engaged in regular rotation for 2-3 years reported the greatest reduction in disease levels (42.30%) ($p = 0.000$). These findings confirm those of Liyama et al. (2022), who noted that crop rotation with non-solanaceous plants minimizes the density of soil-borne inoculum of the pathogen. All other factors remaining constant, fields irrigated by flood irrigation had the highest disease incidence (66.48%). Fields where irrigation is done using drip or sprinkler irrigation had a significantly lower disease incidence (40.87%) ($p = 0.002$). This suggests that flood irrigation disseminates pathogens through likely contaminated surface water, as noted by Mwaniki et al. (2019) and Sharma et al. (2022).

Nutrient management also emerged as a critical factor. Increased nitrogen application, for instance, resulted in higher disease incidence (63.42%) compared with balanced NPK fertilization (49.38%) ($p = 0.004$). Similar results were reported by Ali et al. (2022), who found that excess nitrogen weakened plant defense mechanisms and created favorable conditions for bacterial wilt. The study also revealed that field sanitation measures were very crucial to the spread of the disease. In farms where tools and equipment were not cleaned, disease incidence was highest (65.90%), whereas in farms where sanitation was practiced, reported disease levels were much lower (40.20%) ($p = 0.000$). This supports the findings of Tessema & Seid (2023), which emphasize that uncleaned farm tools are a significant means of pathogen spread. Last, the use of resistant varieties was profoundly associated with reduced disease incidence. Farmers using resistant potato varieties recorded much lower bacterial wilt incidence (44.72%) compared with those

using susceptible varieties (63.81%) (p = 0.000). These findings also agree with the study by Khairy et al. (2021), in which the authors described resistant hosts to bacterial wilt as the most practical and long-lasting means of controlling the disease.

In summary, the use of certified seeds, crop rotation, balanced fertilization, cover crops, and resistant varieties, along with improved integrated drip irrigation and strict crop sanitation measures, can minimize the incidence of bacterial wilt and increase potato yields.

Table 4: Relationship between Farm Management Practices and Potato Bacterial Wilt Incidence (n = 225)

Farm Practice	Category	Mean Disease Incidence (%)	SD	F / t-Value	p-Value
Seed Source	Saved seed	64.85	11.24	7.89	0.001 **
	Local market	59.32	10.47		
	Certified (Govt. agencies)	48.21	9.88		
	Certified (Private companies)	45.78	8.94		
Crop Rotation Practice	No rotation (continuous potato)	67.50	12.15	12.46	0.000 **
	Occasional rotation	55.20	10.96		
	Regular rotation (2–3 years)	42.30	9.35		
Irrigation Method	Flood irrigation	66.48	11.72	9.87	0.002 **
	Furrow irrigation	54.65	10.48		
	Drip/Sprinkler irrigation	40.87	9.13		
Fertilizer Application	Excessive nitrogen use	63.42	11.03	6.15	0.004 **
	Balanced (NPK recommended)	49.38	9.25		
	Random/unplanned application	57.80	10.17		
Field Sanitation	No cleaning	65.90	11.45	10.36	0.000 **
	Occasional cleaning	52.75	10.02		
	Regular cleaning	40.20	8.86		
Use of Resistant Varieties	Yes	44.72	8.94	-8.19	0.000 **
	No	63.81	11.32		

Note:

- Significance levels: *p < 0.05 = Significant*, p < 0.01 = Highly Significant
- F-values were used for variables with more than two categories (ANOVA).
- t-values were used for variables with two categories (Independent t-test).

Chi-square (χ^2) analysis

-The study identified a strong correlation between management practices and educational achievement (χ^2 = 15.67; p = 0.001). This means that farmers with a certain level of educational attainment appreciate the value of management and preventive measures, such as crop rotation, the use of certified seeds, and field sanitation. Having some education means farmers would have little trouble accessing and understanding agricultural educational materials and would be more proactive in making rational decisions in disease management. This is supported by the work of Kwambai et al. (2024), which identified education as a primary determinant of the adoption of technology and improved agricultural practices in developing countries. Farm size was also found to be significant (χ^2 = 12.48; p = 0.002), which means that bigger farms enjoy greater availability of resources such as better quality farming inputs, equipment, and labor, which makes it easier for them to implement integrated management practices. It is also easier for larger farms to appreciate the value of disease control and the long-term justification for spending money on the preventive measures. This is supported by Ali et al. (2022), who noted that resource availability is the primary factor in the adoption of new practices in potato production systems.

Table 5: Chi-square (χ^2) Test Results Showing Association Between Socio-economic Factors and Adoption of Management Practices (n = 225)

Variable	χ^2 Value	df	p-Value	Significance
Education Level	15.67	3	0.001	Highly Significant
Farm Size	12.48	2	0.002	Highly Significant
Farming Experience	8.74	2	0.013	*Significant*
Access to Extension Services	25.12	1	0.000	Highly Significant

Note:

- p < 0.05 = Significant, p < 0.01 = Highly Significant
- df = Degrees of Freedom
- Adoption of management practices includes certified seed use, crop rotation, field sanitation, and planting resistant varieties.

Farming experience was associated with a significant relationship (χ^2 = 8.74; p = 0.013), suggesting that experienced farmers know more about the symptoms and economic consequences of bacterial wilts, which drives them to use effective control methods. Farmers often draw on the vast reserves of knowledge they have gained from farming experience, which also helps them manage pests and diseases (Tafesse et al., 2018). The availability of extension services showed the highest correlation with adoption (χ^2 = 25.12; p = 0.000), indicating that farmers

with more frequent contact with extension workers were more likely to adopt recommended practices such as the use of resistant varieties, improved field sanitation, and balanced fertilization. This supports the findings of Zhang et al. (2022) and Izuogu et al. (2024), who noted the importance of institutional support and knowledge in driving adoptions. In general, the findings imply that increasing education, improving extension services, and supporting resource-poor farmers would increase the adoption of strategies to control bacterial wilt. This highlights the need for institutional support, along with farmer education, to control soil-borne diseases such as Ralstonia solanacearum.

Conclusion

Farmers' management practices are crucial in determining the incidence and the spread of bacterial wilt of potatoes (Ralstonia solanacearum) in District Okara, Punjab, Pakistan. It was found that reliance on uncertified and farm-saved seed, continuous potato monocropping, flood irrigation, excessive nitrogen application, and slack field sanitation are the greatest contributors to the high disease incidence. In contrast, the farms growing certified seeds, practicing crop rotation, drip irrigation and regular tool sanitation reported substantially reduced bacterial wilt prevalence. Results show that integrating disease management strategies helps reduce the prevalence of the disease. Level of education, farm size, years of agricultural practice, and extension services offered were found to have a significant impact on the adoption of recommended practices. In general, more educated farmers and those with better extension contact were found to be more aware and to adopt more sustainable management practices. Hence, disease control requires more farmer training, distribution of certified seeds and resistant varieties, and more extension services. Addressing these issues would promote sustainable potato production, reduce disease control costs, and improve food security and income for the rural population in Punjab, other Indian states, and beyond.

Declarations

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Conflicts of Interest

Authors have no conflicts of interest.

Data Availability

Data will be available from the corresponding author upon request.

Ethics Statement

The Department of Entomology and the Faculty of Agriculture at the University of Agriculture, Faisalabad, approved the human subjects study. The studies were carried out in compliance with institutional norms and local laws. To take part in this study, subjects provided written informed consent.

Authors' Contribution

Ali Nawaz; Conceptualization, Data Curation, Methodology, Writing Original draft, Formal Data Analysis, Writing, Jahanzeb Ali; Review and Editing, Bilal Nadeem; Review, Editing and Writing

Generative AI Statements

The authors confirm that no generative artificial intelligence-based tools were employed for content generation or interpretation. All intellectual content, interpretations, and conclusions are the sole responsibility of the authors.

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REFERENCES

Adnani, M., El Hazzat, N., Msairi, S., El Alaoui, M. A., Mouden, N., Selmaoui, K., Benkirane, R., Ouazzani Touhami, A. O., & Douira, A. (2024). Exploring the efficacy of a *Trichoderma asperellum*-based seed treatment for controlling *Fusarium equiseti* in chickpeas. *Egyptian Journal of Biological Pest Control, 34*(7). https://doi.org/10.1186/s41938-024-00771-x

Akiko, F., Taketo, U., Kentaro, I., & Hiroshi, S. (2019). *Ralstonia solanacearum* colonization of tomato roots infected by *Meloidogyne incognita*. *Journal of Phytopathology, 167*(6), 345–353. https://doi.org/10.1111/jph.12801

Ali, M., Hussain, S., & Raza, A. (2023). Socio-economic factors affecting the adoption of potato production technologies in Punjab, Pakistan. *Pakistan Journal of Agricultural Sciences, 60*(1), 45–53. https://doi.org/10.21162/PAKJAS/2023/112372

Anoumaa, M., Kanmegne, G., Suh, C., Koum, E. B., Sime, H. D., Deloko, C. D. T., & Fonkou, T. (2022). Resistant genotypes combined with high elevation levels provide bacterial wilt control in potatoes (*Solanum tuberosum* L.) in the Western Highlands zone of Cameroon. *Crop Protection, 160*, 106046. https://doi.org/10.1016/j.cropro.2022.106046

Assefa, E. D. (2020). *Social-institutional problem dimensions of late blight and bacterial wilt of potato in Ethiopia: The contribution of social learning and communicative interventions to collective action* (Doctoral dissertation, Wageningen University & Research).

Atieno, E. O., Kilwinger, F. B. M., Almekinders, C. J. M., & Struik, P. C. (2023). How Kenyan potato farmers evaluate the seed: Implications for promoting certified seed potato. *Potato Research, 66*, 811–829. https://doi.org/10.1007/ s11540-022-09602-8

Belay, A., Oludhe, C., Mirzabaev, A., Recha, J. W., Berhane, Z., Osano, P. M., Demissie, T., Olaka, A. L., & Solomon, D. (2022). Knowledge of climate change and adaptation by smallholder farmers: Evidence from southern Ethiopia. *Heliyon, 8*(12), e12089. https://doi.org/10.1016/j.heliyon.2022.e12089

Bereika, M. F. F., Moharam, M. H. A., Abo-Elyousr, K. A. M., & Asran, M. R. (2020). Control of potato brown rot and wilt disease caused by *Ralstonia solanacearum* using some water plant extracts. *Journal of Sohag Agriscience (JSAS), 1*, 30–47.

Buja, I., Sabella, E., Monteduro, A. G., Chiriacò, M. S., De Bellis, L., Luvisi, A., & Maruccio, G. (2021). Advances in plant disease detection and monitoring: From traditional assays to modern tools. *Frontiers in Plant Science, 12*, 716871. https://doi.org/10.3389/fpls.2021.716871

Devaux, A., Goffart, J. P., Petsakos, A., Kromann, P., Gatto, M., Okello, J., & Hareau, G. (2020). Global food security: Contributions from sustainable potato agri-food systems. In *The Potato Crop* (pp. 3–35). Springer. https://doi.org/10.1007/978-3-030-56993-51

Elphinstone, J. (2005). The current bacterial wilt situation: A global view. In C. Allen, P. Prior, & A. C. Hayward (Eds.), *Bacterial wilt disease and the Ralstonia solanacearum species complex* (pp. 9–28). APS Press.

FAOSTAT. (2022). *FAOSTAT statistical database: Agricultural data*. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat

Food and Agriculture Organization (FAO). (2022). *World food and agriculture – Statistical yearbook 2022*. FAO. https://doi.org/10.4060/cc22111en

Gobena, S. T. (2020). *Understanding and managing bacterial wilt and late blight of potato in Ethiopia: Combining an innovation systems approach and a collective action perspective* (Doctoral dissertation, Wageningen University).

Hayes, M. M., Ronnie, J. D., Lavanya, B., Rebecca, M., & Caitilyn, A. (2022). Validating methods to eradicate plant-pathogenic *Ralstonia* strains reveals that growth *in planta* increases bacterial stress tolerance. *Microbiology Spectrum, 10*(6), e02270-22. https://doi.org/10.1128/spectrum.02270-22

Hussain, M., Bukhari, S. A. A., & Ahmad, I. (2022). Determinants of smallholder farmers' technology adoption in potato production in Punjab, Pakistan. *Sarhad Journal of Agriculture, 38*(3), 620–628. https://doi.org/10.17582/journal.sja/2022/38.3.620.628

Izuogu, C. U., Njoku, L. C., Azuamairo, G. C., Oparaojiaku, J. O., Orji, J. E., Njoku, J. I. K., Chinaka, I. C., & Ankrumah, E. (2024). Farmers' attitudes toward certified rice seeds in Ebonyi State. *Journal of Agricultural Extension, 28*(3), 124–133. https://doi.org/10.4314/jae.v28i3.10

Kapalasa, E., Mwenye, O., Jogo, W., Parker, M., & Demo, P. (2022). *Potato value chain analysis report for Malawi*. International Potato Center.

Karacic, V., Miljakovic, D., Marinkovic, J., Ignjatov, M., Miloševic, D., Tamindžic, G., & Ivanovic, M. (2024). Bacillus species: Excellent biocontrol agents against tomato diseases. *Microorganisms, 12*(457). https://doi.org/10.3390/microorganisms12030457

Karlsson, G. K., Stenberg, J. A., & Lankinen, Å. (2020). Making sense of integrated pest management (IPM) in the light of evolution. *Evolutionary Applications, 13*(8), 1791–1805. https://doi.org/10.1111/eva.13067

Kinyua, Z. M., Bararyenya, A., Schulte-Geldermann, E., Obura, B. O., Kashaija, I. N., Tindimubona, F., Opio, D., Oyena, I., Rwomushana, I., Muriithi, W. M., Kinoti, J., Namugga, P., Kimoone, G., Inamahoro, M., Niko, N., & Ndayihanzamaso, P. (2022). Overcoming seed potato quality constraints to tackle food insecurity and poverty in Eastern and Central Africa in the 21st century. ASARECA. https://www.asareca.org

Kithome, M. M., Mogaka, H. R., Mugwe, J. N., & Isaboke, H. N. (2022). Factors influencing adoption of irrigation technologies among smallholder farmers in Machakos County, Kenya. *Journal of Agricultural Extension, 26*(3), 42–52. https://doi.org/10.4314/jae.v26i3.5

Korir, C. K., Christopher, O. G., Paul, O. O., Michael, E. O., & Kibet, N. (2020). Factors affecting adoption of value addition practices among smallholder Irish potato farmers in Bomet County, Kenya. *International Journal of Agricultural Marketing, 7*(1), 225–232.

Kwambai, T. K., Denis, G., Paul, C. S., Laura, S., Rono, S., Caroline, B., Nyongesa, M., & Monica, G. (2024). Seed quality and variety preferences amongst potato farmers in north-western Kenya: Lessons for the adoption of new varieties. *Potato Research, 67*, 185–208. https://doi.org/10.1007/s11540-023-09626-8

Liu, H., Li, T., Li, Y., Wang, X., & Chen, J. (2022). Effects of *Trichoderma atroviride* SG3403 and *Bacillus subtilis* 22 on the biocontrol of wheat head blight. *Journal of Fungi, 8*(1250). https://doi.org/10.3390/jof8121250

Liyama, K., Michishita, R., Arima, H., Kyaw, H. W. W., Yano, K., Horita, M., Tsuchiya, K., & Furuya, N. (2022). Possible invasion pathway of *Ralstonia pseudosolanacearum* race 4 in the ginger plant. *Journal of General Plant Pathology, 88*, 246–250. https://doi.org/10.1007/s10327-022-01068-y

Mwaniki, P. K. (2019). *Status of potato bacterial wilt in Nakuru County (Kenya) and its management through crop rotation and soil amendments* (Master's thesis, Egerton University).

Parveen, S., Mahmood, A., & Azam, M. M. A. (2022). Prevalence of concurrent infections in broiler population of district Chakwal, Pakistan. *Sarhad Journal of Agriculture, 38*(2), 480–488. https://doi.org/10.17582/journal.sja/2022/38.2.480.488

Sharma, K., Fernanda, I. B., Abdulwahab, A., Ricardo, I. A. B., Karen, A. G., Erica, M. G., George, N., Jan, K., Elly, A., & Florence, M. (2022). *Ralstonia* strains from potato-growing regions of Kenya reveal two phylotypes and epidemic clonality of phylotype II sequevar 1 strains. *Phytopathology, 112*(10), 2072–2083. https://doi.org/10.1094/PHYTO-12-21-0525-R

Tafesse, S., Damtew, E., Van Mierlo, B., Lie, R., Lemaga, B., Sharma, K., Leeuwis, C., & Struik, P. (2018). Farmers' knowledge and practices of potato disease management in Ethiopia. *NJAS - Wageningen Journal of Life Sciences, 86-87*, 25–38. https://doi.org/10.1016/j.njas.2018.04.002

Tessema, G. L., & Seid, H. E. (2023). Potato bacterial wilt in Ethiopia: History, current status, and future perspectives. *PeerJ, 11*, e14661. https://doi.org/10.7717/peerj.14661

Wang, Z., Luo, W., Cheng, S., Zhang, H., Zong, J., & Zhang, Z. (2023). *Ralstonia solanacearum* – A soil-borne hidden enemy of plants: Research development in management strategies, their action mechanism and challenges. *Frontiers in Plant Science, 14*, 1141902. https://doi.org/10.3389/fpls.2023.1141902

Yao, X., Guo, H., Zhang, K., Zhao, M., Ruan, J., & Chen, J. (2023). *Trichoderma* and its role in biological control of plant fungal and nematode diseases. *Frontiers in Microbiology, 14*, 1160551. https://doi.org/10.3389/fmicb.2023.1160551

Zhang, Y., Wa, S., Zhang, L., & Lv, C. (2022). Automatic plant disease detection based on a tranvolution detection network with GAN modules using leaf images. *Frontiers in Plant Science, 13*, 875693. https://doi.org/10.3389/fpls.2022.875693