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Combined effects of fungicides formulations and potato varieties on late blight management, yield and net farm income in Kenya

J. M. Kilonzi · M. W. Nyongesa · R. L. Amata · P. Pwaipwai · D. Githui · S. Omondi · W. Lusike · V. Kirugua · J. J. Mafurah

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Abstract Management of late blight relies on the use of fungicides and potato varieties which have been associated with loss of efficacy over time. Baseline survey and field studies were conducted to evaluate the effects of fungicide formulations and potato varieties in managing late blight and subsequently on net farm income improvement. Four fungicides formulations (Infinito® (Fluopicolide 62.5g L^{-1} + propamocarb 625 g L^{-1}), Milraz® (Propineb 700 g kg^{-1} + cymoxanil 60 g kg^{-1}), Mistress 72® (Mancozeb 640 g kg^{-1} + cymoxanil 80 g kg^{-1}) and Ridomil® (Metalaxyl 40 g kg^{-1} + mancozeb 640 g kg^{-1})), and varieties (Kenya Mpya, Shangi and Dutch Robijn) were evaluated. Survey results revealed that the majority (78%) of the farmers selected varieties to grow based on market dynamics as compared to seed availability (18%), disease resistance (12%) and other factors (8%). The most widely and least used fungicides were Ridomil® (28.8%) and Infinito® (1.7%) respectively. Late blight significantly reduced crop growth (height and stem count) and yield in the unprotected plots in Shangi and Dutch Robijn, but no effect was observed in K. Mpya. Mistress® suppressed blight symptoms by 54%, while Milraz® (lowest effects) reduced the disease by (43%). In unprotected plots, disease severity on K. Mpya was below 1%, while in Shangi and Dutch Robijn varieties, it was 60 and 78% respectively. Reduction in disease by Mistress® resulted in higher yield (30.70 t ha^{-1}) as compared to the unprotected plots (9.25 t ha^{-1}). Maximum yield (28.56 t ha^{-1}) was obtained from K. Mpya, while Dutch Robijn, had the lowest observed yield (20.70 t ha^{-1}) in protected plots. Yet, the highest cost benefit ratio (CBR) was recorded in unprotected plots with K. Mpya. The smallest CBR (1.55) was observed on plots where Milraz® was applied on Dutch Robjn. Results of this study show that, the use of fungicides reduced late blight and improved yield of potato substantially, but the efficacy varied with fungicide formulation and potato variety. However, the use of resistant variety was effective in managing late blight hence a useful tool for minimizing fungicide applications. Therefore, use of resistant variety could enhance a healthy biodiversity and at the same time maximize food production.

J. M. Kilonzi (✉) · M. W. Nyongesa · P. Pwaipwai · D. Githui
Kenya Agricultural and Livestock Research Organization (KALRO), Tigoni, P. O. BOX 338-0217, Limuru, Kenya
e-mail: kilonzijack@gmail.com

R. L. Amata
Kenya Agricultural and Livestock Research Organization (KALRO) Kabete, National Agricultural Research Laboratories, P.O BOX 14733-00800, Nairobi, Kenya

S. Omondi · W. Lusike · V. Kirugua
Kenya Agricultural and Livestock Research Organization (KALRO), Headquarters, P.O BOX 57811-00200, Nairobi, Kenya

J. J. Mafurah
Egerton University, P.O BOX 536-20115, Egerton, Njoro, Kenya

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Introduction

Potato (*Solanum tuberosum*) is an important food crop consumed widely. The tuber crop is a major source of income for smallholder farmers in most potato growing regions. Yet, the resource restrained farmers are often constrained by a number of factors including, poor access to certified seed, poor agronomic practices, low farm gate prices and biotic stress (Schulte-Geldermann et al., 2012). Late blight (*Phytophthora infestans*); a major biotic stress of potato, is the most devastating disease of the tuber crop. The Irish potato famine of the 1840s had the most significant impact of late blight globally (Ristaino, 2002). Globally, the annual economic losses attributed to the disease is about 170 US billion dollars (Haverkort et al., 2008). The fungal disease therefore remains a threat to food security, despite historical advancement in exploration for sustainable solutions (Haas et al., 2009). In Kenya, late blight is a key disease due to its detrimental impacts on the ware and seed potato industry (Olanya et al., 2006). Recent research showed that, the disease can potentially cause up to 100% yield loss in Kenya, if left uncontrolled on susceptible varieties and when conducive weather conditions prolonged. (Kilonzi et al., 2020). The prolonged weather conditions are common features of potato growing areas (highlands).

The sub-sector employs about 1.8 million people directly and over 0.8 million actors indirectly, hence forming a key income generating activity in Kenya (Kwambai et al., 2023). Increased urbanization has presented opportunities for the potato industry. Nutritionally (per 100 g), the tuber crop provides high starch content (16.1 g), potassium (443 mg), proteins (2.1 g), vitamin C (17.1 mg) and essential amino acids (Beals, 2019). Thus, potato could be a reliable alternative in improving health and nutrition of the rural population, since the crop has higher production per unit area than cereals in the highland areas of Rift valley, Central and Western Counties of Kenya (Mariita et al., 2016).

Data on the diversity of *P. infestans* populations in Kenya are sparse, introducing uncertainties in developing effective disease management programs. The latest study in the best of our knowledge is by Njoroge et al. (2019). The research showed that, genotypes of *P. infestans* in Kenya are dominated by US_1 clonal lineage and European genotype (2_A1). Introduction of these genotypes could be associated with the global potato trade. The successes of *P. infestans* in the field are attributed to its co-evolution with the newly released resistant potato varieties (Zhu et al., 2012), ability to adapt to systemic fungicides (Matson et al., 2015) and development of new stable and resilient strains (Beninal et al., 2022). Moreover, the mode of spread of the pathogen is diverse, ranging from primary (infected seed tubers, volunteer crops, potato debris and cull piles) to secondary (spread by wind from neighbouring infected fields) sources (Lima et al., 2009). Previous research showed that, continuous cultivation of potato, affects the life cycle of the pathogen, shortening the duration of each stage of the fungi cycle (Tafesse et al., 2018). This facilitates enhanced transmission of the disease from season to season and from region to region. In addition, the fungus seems to adapt to changing environmental conditions (Brasier et al., 2022). Even though, favourable weather conditions showed that, *P. infestans* thrives in a temperature range of 4 to 19 °C, relative humidity of above 96% and leaf wetness duration of about 3 h (Arora et al., 2014), previous findings have revealed that, the fungi can survive in a wider weather regime (Wu et al., 2020). In addition, previous studies, showed a significant influence of environmental conditions to the biology of *P. infestans* (Miller et al., 2015), implicating the efficacy of the current biological control strategies. Thus, there is a need to re-evaluate the available tools of control including fungicide formulations.

The use of fungicides and varietal resistance has played a key role in reducing late blight epidemics (Ritchie et al., 2018). However, stable host resistance and fungicide insensitivity is a major concern. To optimize efficacy of the fungicides, some potato growers increase fungicide dosage and application frequency (Taylor et al., 2013), which often implicate the trade-offs between yield improvement, and the cost of production (Rani et al., 2021). The use of fungicides has become costly and is often associated with environmental and human exposure concerns (Devaux et al., 2014). Notably, the choice of variety is influenced by market demand forces rather than their response to biotic stresses (Muthoni et al., 2013). Moreover, some of the resistant potato varieties previously released as resistant/tolerant have succumbed to *P. infestans* strains. For instance, in Kenya, the Asante potato variety (also called Victoria in Uganda) (Forbes, 2012) and Tigoni, were previously released as tolerant varieties to late blight, but today, are now in the susceptible category (personal observation over 8 years). On the other hand, some fungicides which were initially effective and adopted by farmers, have lost their efficacy due to the development of less sensitive strains over time (Schepers et al., 2018). For example, resistance to metalaxyl reported in 1977 (Davidse et al., 1988) attributed to the extensive use of the chemical to manage late blight. Unexpectedly, metalaxyl insensitive genotypes were reported in the mid-1990s in USA and Canada few years later (Goodwin et al., 1996). Since then, the metalaxyl-resistant isolates have been reported in a number of potato growing regions globally (Mugao et al., 2021; Gunacti et al., 2019; Matson et al., 2015; Childers et al., 2014; Solano et al., 2014; Wang et al., 2012; Pérez et al., 2009; Fontem et al., 2005). Recently, Muchiri et al. (2017) findings showed significant contribution of chemical mixtures in managing late blight and improvement in net income as compared to single molecule formulated fungicide. Despite these interventions, the disease remains a major challenge in potato production, requiring application of fungicides at short intervals (Ivanov et al., 2021). This approach is insufficient and unsustainable. Studies on the use of biocontrols (El-Hasan et al., 2022), seed dressing (Wharton et al., 2012), cultural practices (Hussain et al., 2013) and integrated late blight management (Sedlák et al., 2022); Khadka et al. (2020); Kassaw et al. (2021) have also been proposed. Unfortunately, biocontrol methods (one of the eco-friendly approaches) are not yet effective to suppress the disease (Yao et al., 2016; Kilonzi et al., 2020).

In the present study, we focus on re-evaluating chemicals formulations and potato varieties common among farmers in Kenya. The aim of this work, is to provide a baseline knowledge on the efficacy of current chemical formulations in Kenyan market and demonstrate the need for integrating chemical formulations and resistant varieties in late blight management program. We therefore hypothesize that, i) different fungicides and potato varieties are utilized by potato farmers, ii) variations in fungicide formulations will influence late blight symptom progression in different potato varieties, and that, iii) dynamics on potato crop growth (height and number of stems), yield and net farm income improvement will be attributed to the management of late blight associated with fungicide formulations and varietal differences.

Materials and methods

Survey on common fungicides among potato growers

To assess the fungicide formulations and their utilization in managing late blight, a baseline survey targeting only potato farmers who grew potato in the previous season was conducted in August 2020 to generate primary data. The study was done in Nyandarua County, Kenya from three sub counties namely; North Kinagop, South Kinangop and Ol-Kalou. The sub counties are the most important potato producing regions in Kenya (Agong et al., 2021). A total of 89 out of 20,000 potato growing families were randomly selected to participate in the study. Face to face interviews were conducted using a pre-tested semi-structured questionnaire. Demographic and socioeconomic data, choice of variety, fungicides formulations commonly used, cost of fungicide application, daily wage, land hire, production statistics and fungicide application regimes were assessed. Data collected were compared with secondary sources including previous studies and county annual reports for validation.

Field experiment

A field experiment was conducted from 2021 to 2022 which coincided with short and long rain seasons. The trials were laid in two experimental sites namely; Kenya Agricultural and Livestock Research Organization (KALRO) Tigoni field, Limuru, Kiambu County and Njabini in Nyandarua County. Tigoni is located at an altitude of 2,300 m above sea level, latitude 10° 9´ 22˝ south and longitude 36° 4´ 72˝ east, while Njabini is located at latitude 0.1804° S and longitude 36.5230°E. It lies at co-ordinates 0° 10′ 49.39" S and 36° 31′ 22.67" E. Both sites receive bimodal rainfall pattern. KALRO Tigoni receives an average rainfall amount of about 1800 mm per annum and temperature ranges from 10 to 25 °C. The altitude of Njabini is 2564 m above sea level. Average amount of rainfall received in Njabini is 2000 mm per annum and the site experiences temperature range of between 8 to 24 °C (Jaetzold et al., 2006).

Experimental materials and field management practices

Varieties used in this experiment were; Shangi (Moderate susceptible), Dutch Robijn (susceptible) and Kenya Mpya (tolerant variety used as positive check) of basic seed generation. The varieties were selected based on farmers' preference from survey results and their response to late blight. Seeds of size 45 mm were obtained from KALRO Tigoni, whilst fungicides (selected based on survey results), were obtained from local shop. The fungicides included the ones that had the highest frequency of utilization (Milraz®, Mistress 72® Ridomil®) and compared to the one least used (Infinito®). Infinito® was selected because of its unique co-formulation as compared to the other fungicides. The chemicals brief descriptions are presented in Table 1.

Land preparation was conducted during dry periods of each cropping season to pulverize the soil and remove weeds. Furrows were prepared at a spacing of 75 cm and 20 cm deep using a hoe. Diammonium Phosphate (DAP) fertilizer was applied at a rate of 500 kg ha^{-1} along the furrows. Upon mixing the fertilizer with soil, seed tubers were planted on the first week after onset of rains at spacing of 30 cm apart. Top dressing was applied at a rate of 250 kg ha^{-1} using Calcium Ammonium Nitrate (CAN) 25 days after emergence. Standard field management practices (weed and insect pest management) were applied uniformly throughout the cropping seasons. Hilling was conducted after 25 and 45 days of emergence (DAE) uniformly in all the experimental plots.

Experimental design

Experimental treatments were laid in a randomized complete block design in split plot arrangement replicated three times. The main plots and sub-plots were varieties and fungicide formulations respectively. The sub-plots measured 3 × 3 m, separated by a path measuring 1.5 m wide. Disease initiation on the potato foliage relied on natural infection. Fungicide application was started when the first symptoms were observed and subsequently on a weekly basis. Fungicide drifts were managed using two iron sheets measuring 2 m long by 1 m width placed along the two adjacent rows while spraying. The fungicide rate was as recommended by the manufacturers (Table 1). A 20 L pre-calibrated knapsack sprayer was used. Control plots included the unsprayed plots, resistant variety (K. Mpya) and susceptible variety (Dutch Robijn).

Gross margins and cost benefits analysis

Gross margins were calculated as the difference between gross returns (price of potato multiplied with total yield) and total variable costs (all expenses involved in the production of potato). The variable costs included wage pay, land preparation costs, land hire, crop management and crop protection associated expenses. Costs of the fungicides were based on the local retailers' price, while farm gate prices were collected from stations in which the experiment was conducted. To establish the best combinations, cost benefit ratio was calculated using Eq. 1 (Bajracharya & Sapkota, 2017), while marginal rate of return was conducted as shown in Eq. 2

$$\text{Cost Benefitratio} = \frac{\text{Gross profit}}{\text{Total Variables Costs}} \tag{1}$$

The marginal rate of return was calculated using the below formula;

Table 1 List of chemical fungicides and their detailed description used in the study

Trade name	Company	Active ingredient	Rate per hectare	Formulation	WHO class
Ridomil®	Sygenta Co	Metalaxyl 40 + Mancozeb 640 g kg^{-}	2.5 kg	Solid	U
Infinito®	Bayer East Africa	Fluopicolide 62.5 + Propamocarb 625 g L^{-1}	1.5 L	Liquid	III
Mistress®	Osho Chemicals	Mancozeb 640 + Cymoxanil 80 g kg^{-1}	2.0 kg	Solid	U
Milraz®	Bayer East Africa	Propineb 700 + Cymoxanil 60 g kg^{-1}	2.0 kg	Solid	III

$$\mathrm{MRR\%} = \frac{\mathrm{DNI}}{\mathrm{DIC}} \times 100 \tag{2}$$

where, MRR% is the percentage marginal rate of return, DNI is the difference in net income compared with the control (change in net benefits (Net benefits from new technology minus net benefits from control)) and DIC is the difference between input cost compared to control (Change in total variable costs (Total variable cost of new technology minus control)).

Data collection

Rainfall data (amount) were recorded in both sites from nearby weather stations on a daily basis. Crop growth (height measurement and stem count), disease and yield measurements were collected from the interior rows. Height measurement and stem count was conducted from 30 days after emergence and then fortnightly. Late blight symptom assessment began before initiating fungicide application followed by weekly assessments. Data on disease incidence were converted to percentage disease incidence (PDI) (Eq. 3). Disease severity assessment was based on the percentage of leaf area infected and interpreted as a scoring scale of 1 to 10; where 1was healthy leaf, 2 = up to three lesions, 3 = up to 5% of leaf area, 4 = 5.1 – 10%, 5 = 10.1 – 25%, 6 = 25.1 – 50%, 7 = 50.1 – 75%, 8 = 75.1 – 85%, 9 = 85.1 – 95% and 10 = 95.1 – 100% of leaf area covered with blight symptoms (Andrivon et al., 2006). The disease scores were summarized to percent disease severity (PDS) as shown in Eq. 4. The weekly percentage disease severity (PDS) was used to calculate Area Under Disease Progress Curve (AUDPC) at the end of each cropping season as shown in Eq. 5 (Simko & Piepho, 2012).

$$\mathrm{PDI} = \frac{\text{Number of diseased plants}}{\text{Total number of plant sassessed}} \times 100 \tag{3}$$

$$\mathrm{PDS} = \frac{\Sigma\ \text{individual numerical rating}}{\text{Total number of plant sassessed} \times \text{maximum score in the scale}} \times 100 \tag{4}$$

$$\mathrm{AUDPC} = \sum_{\mathrm{i=1}}^{\mathrm{n\text{-}1}} \left(\frac{y_i + y_i}{2}\right) \times \left(\mathrm{t}_{\mathrm{i+1}} - \mathrm{t}_{\mathrm{i}}\right) \tag{5}$$

where $y_{i,}$ $t_{i,}$ and i^{th} represents assessment of disease (percentage) at i^{th} observation, time (days) at i^{th} observation and i^{th} represent total number of observations respectively.

Marketable tuber size (> 35 mm in diameter) were weighed separately. Yield data was converted to tonnes per hectare before subjecting the data to analysis.

Data analysis

Demographic and socio-economic data collected from the survey were analyzed using Statistical Package for Social Science (SPSS) v. 16 and Microsoft excel. Univariate analysis and two-way (fungicide formulation*variety) analysis of variance was conducted to determine the effect of fungicides, varieties and their combined effects on late blight, crop growth and yield using SAS v. 8.2 software. Treatment means were compared using Tukey honest significant difference ($p \leq 0.05$).

Results

Demographic and fungicides utilization

Our baseline survey results showed that, most of the potato growers were female (62%) and 96% of the farmers depended on potato production as source of food and income. Notably, farmers aged above 60 years were the majority (35%), while young adults (20 – 35 years) were minority (11%) (Table 2). In terms of the level of education, 55% of the farmers completed secondary school, whilst only 4% had no elementary education

Table 2 Frequency distribution of age of the respondents

Age of farmer (years)	Frequency (%) *n = 89*
20 – 35	11
36 – 40	19
41 – 50	13
51—60	22
> 61	35

Table 3 Frequency of education level of the respondents

Education	Frequency (%) *n* = *89*
Tertiary	6
Completed secondary	55
Incomplete secondary	6
Primary	29
No elementary education	4

Table 4 Frequency of land size dedicated for potato production by respondents

Land size (ha)	Frequency (%) *n* = *89*
< 0.5	27
0.5 – 1.0	63
1.1 – 2.0	6
> 2.1	4

(Table 3). Most of the field sizes for potato production ranged from 0.5 to 1.0 ha (63%), followed by 0.5 ha (27%) (Table 4). Market dynamics was the key factor (78%) used by the respondents to determine the choice of potato variety, while seed availability and resistance to late blight contributed to 18% and 12% to their decision, respectively. Other factors which included, fellow farmer donations, purchase from neighbours and recycling their own seed informed about 2% on choice of variety (Fig. 1). Ridomil® and Mistress 72® were the most widely used fungicides by 28.8% and 22.0% of the respondents respectively, followed by Zetanil® (Cymoxanil 6% and Mancozeb 70%) which was used by about 17% of the potato growers. Equation®, Flyee®, Vanguard®, and Infinito® were the least (1.7%) used fungicides (Table 5). About 80% of the respondents applied the chemicals on a weekly spray interval and about 20% applied biweekly. Less than 5% of the respondents suggested that they had no uniform application regime.

Weather and late blight incidence

During the experimental period, the amount of rainfall and relative humidity was variable. The highest average amount of rainfall during the assessment period was 350 mm observed in the long rain season (Fig. 2a). The short rain season generally had higher rainfall amounts during the assessment period especially from day 56 after emergence to the end of the cropping season (Fig. 2b). Njabini site seemed to have higher rainfall in both seasons than Tigoni. Relative humidity trends were not correlated with rainfall observations. In Njabini, the long rain season had higher relative humidity (RH) than in the short rain season. On the other hand, the short rain season generally had higher RH than the long rain season in Tigoni (Fig. 2c). There was a decline in both rainfall and relative humidity towards the end of cropping season. Water-soaked lesions covered with white mycelia mass and circular light green patches were first observed on the foliage of the susceptible variety (Dutch Robjin) in first week after emergence. Despite the variable weather conditions in both seasons, the percent disease incidence (PDI) attained 100% score in Njabini. In Tigoni, 100% PDI was observed in the long rain season, while in the short rain season PDI was 80%. The highest PDI was recorded between day 14 and 70 after crop emergence; a period when rainfall was high and RH was slightly increasing. Unexpectedly, the disease incidence consistently increased till crop senescence despite the decline in rainfall and RH.

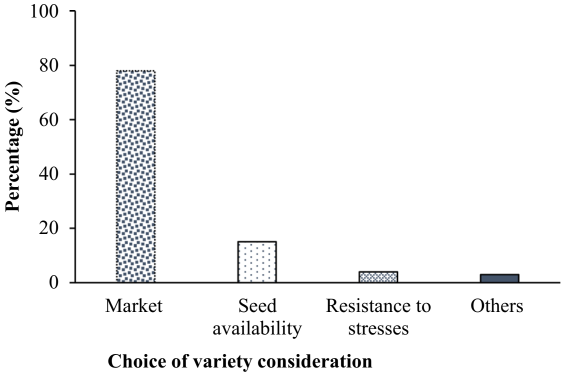


Fig. 1 Factors influencing choice of variety to grow among the respondents

Effects of late blight management on crop growth and performance

Fungicide applications showed significant effects on height measurements on Shangi (Fig. 3a) and Dutch Robjin (Fig. 3b) varieties, but had no effect in

Table 5 Choice of fungicides used by respondents in late blight management

Fungicide	Frequency	Percentage (%)
Ridomil® (metalaxyl 40 g kg^{-1} + mancozeb 640 g kg^{-1})	17	28.8
Mistress® (cymoxanil 80 g kg^{-1} + mancozeb 640 g kg^{-1})	13	22.0
Zetanil® (cymoxanil 60 g/kg + mancozeb 700 g/kg)	10	16.9
Agromax® (cymoxanil 80 g kg^{-1} + mancozeb 640 g kg^{-1})	6	10.2
Tajiri® ((cymoxanil 80 g kg^{-1} + mancozeb 640 g kg^{-1})	3	5.1
Milraz® (Propineb 700 g kg^{-1} + cymoxanil 60 g kg^{-1})	2	3.4
Master® (metalaxyl 80 g kg^{-1} + mancozeb 640 g kg^{-1})	2	3.4
Victory® (metalaxyl 80 g kg^{-1} + mancozeb 640 g kg^{-1})	2	3.4
Equation® (cymoxanil 300 g kg^{-1} + famoxadone 225 g kg^{-1}),	1	1.7
Flyer® (200 g/l pyraclostrobin)	1	1.7
Vanguard® (Cymoxanil 300 g/kg + Famoxadone 225 g/kg)	1	1.7
Infinito® (Fluopicolide 62.5g L^{-1} + propamocarb 625 g L^{-1})	1	1.7
Total	59	100.0

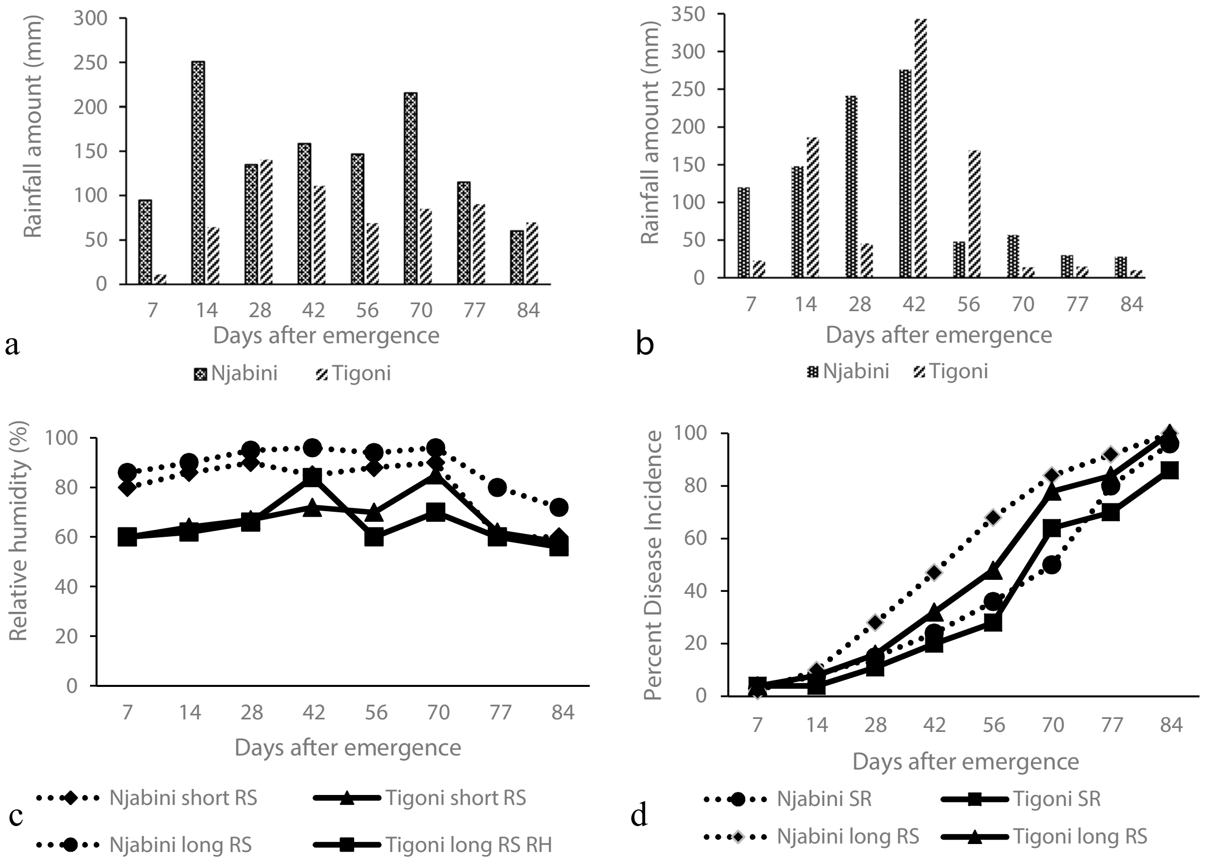


Fig. 2 **a** Rainfall amount during the short rain season of 2021 in Tigoni and Njabini. **b** Rainfall amount during the long rain season of 2022 in Tigoni and Njabini. **c** Relative humidity (%) of both short and long rain season in Tigoni and Njabini

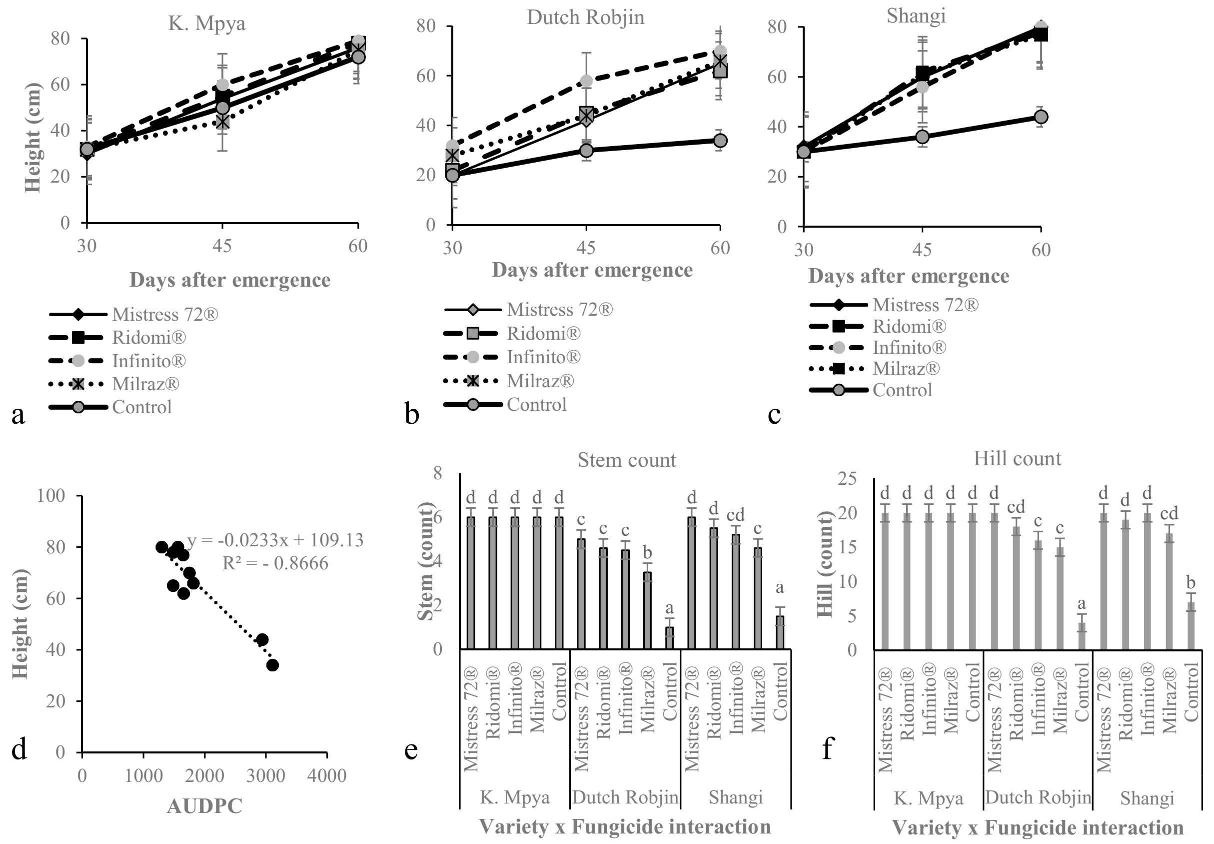


Fig. 3 **a** Effects of fungicides on K. Mpya height growth. **b** Effects of fungicides on Dutch Robjin height growth. **c** Effects of fungicides on Shangi height growth. **d** correlation between the maximum crop height and AUDPC. **e** Effects of fungicides on varietal stem count. **f** Effects of fungicides on hill count

plots with K. Mpya (Fig. 3c). The maximum mean height attained by K. Mpya, Dutch Robjin and Shangi was 80, 62 and 78 cm respectively in maximumly protected plots. The control plot showed the lowest height growth in Dutch Robjin and Shangi, attaining height of 35 and 42 cm respectively. The effects of late blight were further substantiated by the negative correlation (r =—0.75) between the AUDPC and height (Fig. 3d). Variation in stem count was observed among the varieties. Generally, K. Mpya and Shangi had highest maximum stem count (6.5), while Dutch Robjin had the lowest (4.5) in all protected plots. Effects of fungicides on stem count was observed in the Dutch Robjin and Shangi varieties in which mean stem count of 1 and 1.5 were recorded respectively, in the unprotected plots. On the other hand, stem count in control plots associated with K. Mpya was not significantly different from maximumly protected plots. In plots with Dutch Robjin and Shangi, Milraz® had the lowest stem count followed by Infinito®, Ridomil® and Mistress 72® in that order (Fig. 3e). In the interior rows (rows in which data was collected from) in which 20 plants (hills) were planted, K. Mpya consistently maintained this plant population in all the treatments throughout the assessment period, while variation in Dutch Robjin and Shangi was apparent. The number of hills per plot were more than 50% lower in the control plot compared to the protected plots. The performance of the fungicides in contributing to hill counts followed similar trajectory as in the stem count (Fig. 3f).

Late blight severity

Analysis of variance suggested that late blight severity from the two sites was not significantly different ($p \leq 0.05$). Both sites recorded a higher

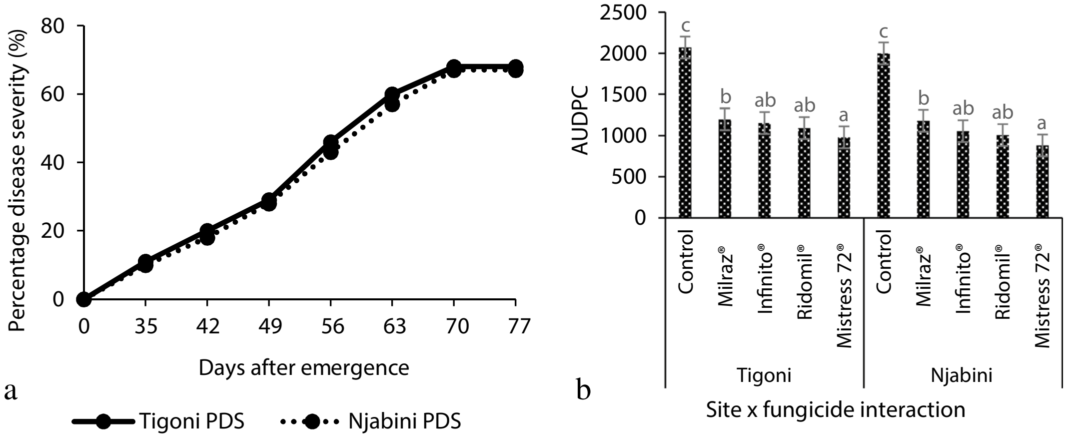


Fig. 4 **a** Percent disease severity across days after emergence in Tigoni and Njabini site from combined short and long rain season data of control plots. **b** Effects of variety and fungicide formulations on AUDPC in Tigoni and Njabini sites in control plots from combined short and long rain season data

disease severity of about 68% (Fig. 4a). Area under disease progress curve (AUDPC) showed that fungicide application affected late blight significantly. The highest (about 2100) AUDPC was observed in Tigoni, while in Njabini AUDPC was about 2000 in the unprotected plots. However, the two control plots were not significantly different. Milraz® had significantly higher AUDPC among the fungicide formulations. Remarkably, Mistress 72®, Infinito® and Ridomil® were not significantly different in both sites and recorded AUDPC range of 750 to 800 (Fig. 4b). Table 6 suggests that the highest disease severity was observed in control plots from day 35 to 77 after emergence. At the initial assessment (28 DAE) before fungicide application, all the plots had the same disease severity score (data not shown). After fungicide application (7 days later), the control plot was already significantly different from plots protected with fungicides. At this moment, the efficacy of the fungicides was not significantly different ($p \leq 0.05$). However, generally, in the succeeding assessment, Mistress 72® showed the lowest disease severity, while Infinito® and Ridomil® were not significantly different (Table 6). During the assessment period, the highest disease severity (77%) was observed on Dutch, Robjin followed by Shangi that had 71%. In affirmation, across the days of assessment, Dutch Robjin had significantly higher disease severity than Shangi, whilst in K. Mpya disease severity was below 2%. Similar results were found for the AUDPC (Table 7). Figure 5 showed that protected and unprotected plots did not differ significantly in plots with K. Mpya (Fig. 5a). Notably, application of fungicide significantly reduced disease on Dutch Robjin (Fig. 5b) and Shangi (Fig. 5c). The unprotected Dutch Robjin and Shangi plots had the highest disease severity compared to the protected plots. However, the

Table 6 Effects of fungicides in managing late blight in combined analysis for the two sites

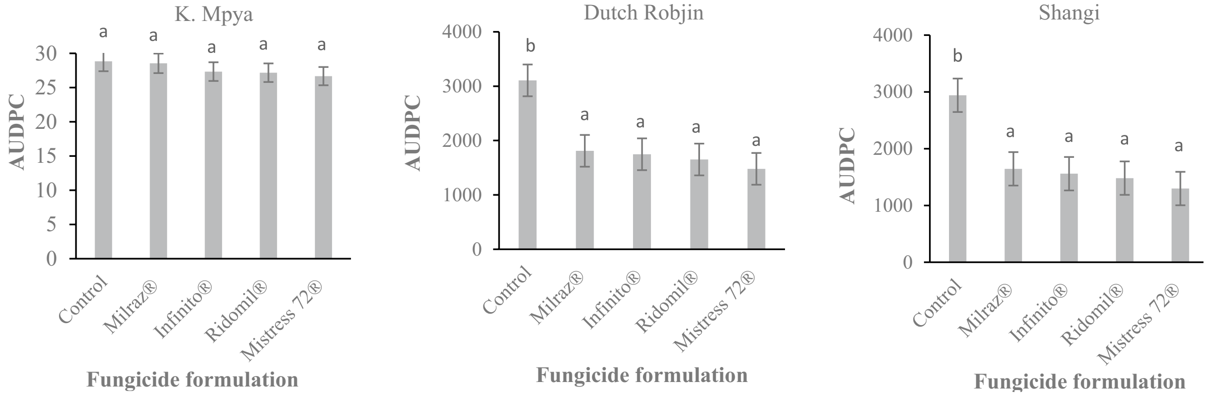
	Disease severity across days after emergence							
Fungicide	35	42	49	56	63	70	77	AUDPC
Control	10.67a	19.11a	28.39a	44.44a	55.56a	67.50a	67.56a	2036.22a
Milraz®	1.61b	5.78b	12.78b	21.72b	32.56b	44.28b	47.78b	1160.11b
Infinito®	1.78b	4.83b	11.28bc	20.83b	30.94b	42.67bc	47.11bc	1110.00bc
Ridomil®	1.22b	4.00bc	9.61cd	19.00bc	29.2c	41.56c	45.72c	1051.61c
Mistress 72®	0.78b	2.61c	7.67d	16.89c	26.00d	36.72d	42.50d	929.61d
HSD($p \leq 0.05$)	1.4120	1.420	3.029	2.993	2.646	2.375	1.933	59.895

Numbers followed by same letter in the same column indicate that the treatments do not differ significantly

Table 7 Effects of variety in managing late blight in combined analysis for the two sites

Variety	Disease severity across days after emergence							AUDPC
	35	42	49	56	63	70	77	
Dutch Robjin	4.78a	12.07a	23.73a	37.90a	57.63a	70.90a	77.27a	1959.33a
Shangi	4.77a	9.73b	17.87b	35.40b	50.43b	67.50b	71.53b	1784.50b
Kenya Mpya	0.0b	0.00c	0.23c	0.43c	0.60	1.23c	1.60c	28.70c
HSD($p \leq 0.05$)	0.941	2.001	1.983	1.753	1.754	1.574	1.281	39.68
CV (%)	27.89	26.57	23.29	13.06	7.98	5.47	4.13	5.107

Numbers followed by same letter in the same column indicate that the treatments do not differ significantly



(a) (b) (c)

Fig. 5 Effects of variety-fungicide interaction on late blight severity for K. Mpya **a**, Dutch Robjin **b** and Shangi **c** from combined data of Tigoni and Njabini

fungicides (Milraz®, Mistress 72®, Infinito® and Ridomil®) were not significantly different in managing disease severity.

Yield and yield components

The yield from the two experimental sites was not significantly different in the potato varieties under study. Yield results showed that, protected plots had significantly higher yield as compared to the unprotected plots. Use of Mistress 72® contributed to significantly higher average tuber weight, marketable and total yield than the other fungicides. Average tuber weights from plots protected using Milraz®, Infinito® and Ridomil® were not significantly different. However, marketable yield from the Milraz® protected plots was lower than that obtained from plots sprayed with Infinito® and Ridomil® (Table 8). In addition, varietal variations contributed to differences in average tuber weight, marketable and total yield. Data from the trio-yield components suggest that K. Mpya had the highest average scores, followed by Shangi and Dutch Robjin in that order (Table 9). In terms of Variety -fungicide interaction, Fig. 6a reveal that, the yield from protected and unprotected plots of K. Mpya were not significantly different. However, fungicides formulations contributed to higher yield during the experimental period. Control plots

Table 8 Effects fungicide on contribution to the yield of potato

Fungicide	Average tuber weight (g)	Marketable yield (t ha^{-1})	Total yield (t ha^{-1})
Control	22.84a	9.25a	9.85a
Milraz®	66.89b	26.07b	26.76b
Infinito®	67.67b	27.60c	27.82bc
Ridomil®	67.94b	27.93c	28.44c
Mistress 72®	70.89c	30.70d	30.90d
HSD($p \leq 0.05$)	2.437	1.369	1.33

Numbers followed by same letter in the same column indicate that the treatments do not differ significantly

Table 9 Effects variety on contribution to the yield of potato

Variety	Average tuber weight (g)	Marketable yield (t ha^{-1})	Total yield (t ha^{-1})
Dutch Robjin	49.17a	20.70a	21.24a
Shangi	58.40b	23.66b	24.02b
K. Mpya	70.17c	28.56c	29.01c
HSD($p \leq 0.05$)	1.614	0.907	1.15
CV (%)	4.410	6.04	5.756

Numbers followed by same letter in the same column indicate that the treatments do not differ significantly

showed the lowest yield (below 5 t ha^{-1}). Its explicit that from Dutch Robjin (Fig. 6b) and Shangi (Fig. 6c) planted plots, the fungicide formulations did not differ significantly.

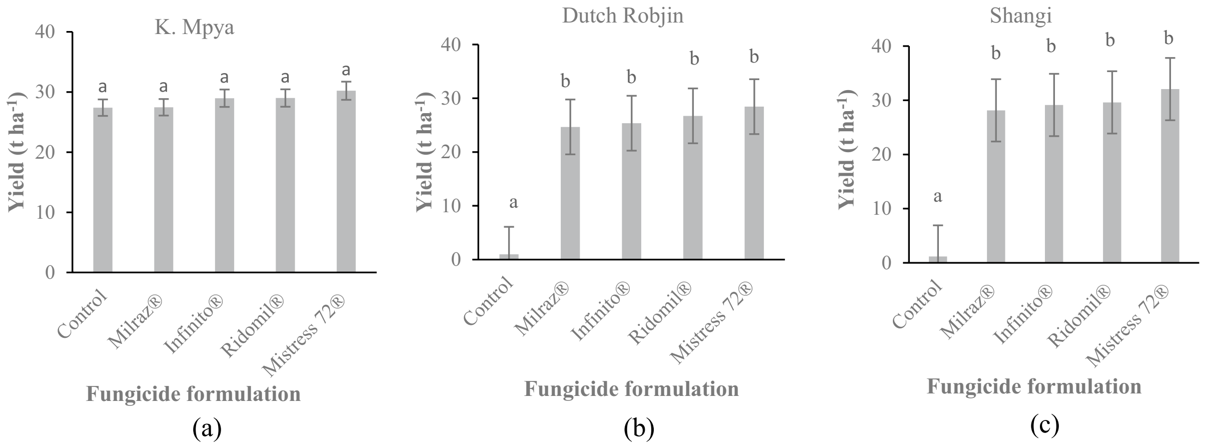
Correlations

Analysis of correlation revealed a strong positive correlation yield of $r^2 = 0.88$ and $r^2 = 0.92$ with stem count (Fig. 7a) and height measurements (Fig. 7b) respectively. AUDPC and total yield component showed a strong negative correlation ($r^2 = -0.98$) (Fig. 7c).

Financial analysis

Costs and revenue

The farm gate prices were USD 14.67 per 100 kg bag of the K. Mpya and Dutch Robjin varieties, whilst the Shangi variety was USD 18.67, according to survey



(a) (b) (c)

Fig. 6 Effects of variety-fungicide interaction on total yield of K. Mpya **a**, Dutch **b** and Shangi **c** varieties. Key: Treatments with the same letter indicate the treatments are not significantly different using error bars

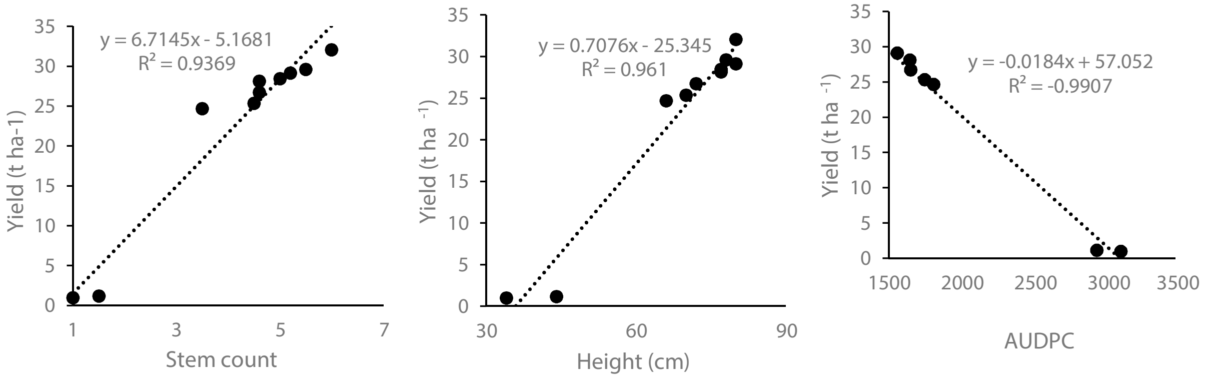


Fig. 7 The correlation between stem count **a**, height measurementas **b**, and AUDPC **c**, and the total yield

Table 10 Costs of inputs applied and utilized for gross profit analysis

Input	Unit	USD (150 Kes = 1 USD)	Source of information
Seed cost	50 kg	21.33	KALRO Tigoni
Wage for field activities (except fungicide application)	Man days	2.00	Extension officers' personal communication (Nyandarua)
Wage for spraying	Man days	4.00	Extension officers' personal communication (Nyandarua)
Ridomil®,	kg	14.67	Local market
Infinito®,	kg	40	Local market
Milraz®	kg	14.67	Local market
Mistress 72®	kg	12	Local market
Duduthrin®	L	12	Local market
Seed transport	Km per tonne	0.67	Limuru transporters
DAP fertilizer	50 kg bag	30	Local market
CAN fertilizer	50 kg bag	20	Local market
100 kg gunny bags	piece	0.40	Local market
Knapsack hire	Per ha	1	Extension officers' personal communication (Nyandarua)

results and in comparison, with agricultural extension officer's market survey report. In one hectare, 44 bags of seed were planted. Insecticide is usually mixed with fungicide during application. A total of 16 man days were used in making furrows and weeding, while 4 man days were required for dehaulming. During the cropping seasons, an average of 6 fungicides applications were applied and 4 man days per hectare were required. According to farmers practice as observed during survey, about 80 L (equivalent to 4 knapsacks of 20 L capacity) of the chemical suspension was required for application per hectare (Table 10).

Gross margins and marginal rate of return

In this section, Milraz® was not considered in the analysis since it showed lower efficacy than the other fungicides. Results of the complete budgeting suggests that the higher yields observed in K. Mpya contributed to higher gross profit than observed in Shangi and Dutch Robjin. The unprotected plots of Dutch Robjin and Shangi resulted to loss. Unexpectedly, the cost benefit ratio (CBR) of unprotected plots was higher (2.12) than the protected plots (1.76) with K. Mpya. In the protected plots, K. Mpya recorded the least marginal rate of return as compared to Shangi and Dutch Robjin varieties. Shangi had the highest marginal rate of return (MRR), followed by Dutch Robjin and then K. Mpya in that order. Notably, application of Mistress 72® resulted in higher MRR than Ridomil® and infinito® in the three varieties. The highest proportion of cost was recorded in the seed procurement, which translated to about 40% of the total cost of production, followed by the cost of DAP fertilizer (17%) (Table 11).

All values are in Kenya shillings unless stated in respective row. Milraz® was not considered since it had the lowest late blight suppression and yield and its price was same as Ridomil®.

DISCUSSION

Our survey revealed that, the majority of the potato growers were aged above 60 years, while young adults were minority. This could be attributed to land ownership where the majority of young people do not own land, or are not interested in farming. Despite this, young asdults are an important proportion of the population key in contributing to food security. The agricultural activities in potato production, often include efficient and timely application of fungicides to manage late blight, which can be affected by human factors such as age (Taiy et al., 2017). Njeru (2017) reported that, active participation of the youth in farming could result in improved food production. In addition, the level of education is a critical aspect in understanding late blight management protocols. For instance,

Table 11 Gross margins, cost benefit and marginal rate of return analysis in using variety in combination with fungicides to manage blight

Activity/ Input ha-1	Fungicide unprotected			Protected Dutch Robjin			Protected Shangi			Protected K. Mpya		
	Dutch Robjin	Shangi	K. Mpya	Mistress®	Ridomil®	Infinito®	Mistress®	Ridomil®	Infinito®	Mistress®	Ridomil®	Infinito®
Yield (t ha-)	0.99	1.17	27.40	28.44	26.73	25.36	32.06	29.61	29.13	32.21	29.00	28.97
Revenue	145.20	218.40	4018.67	4171.20	3920.40	3719.47	5984.53	5527.20	5437.60	4724.13	4253.33	4248.93
Seed	896.00	896.00	896.00	896.00	896.00	896.00	896.00	896.00	896.00	896.00	896.00	896.00
Hired land	166.67	166.67	166.67	166.67	166.67	166.67	166.67	166.67	166.67	166.67	166.67	166.67
Ploughing	91.67	91.67	91.67	91.67	91.67	91.67	91.67	91.67	91.67	91.67	91.67	91.67
Harrowing	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00
Furrowing	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67
Planting	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67
DAP	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Weeding	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67	42.67
Spraying	0.00	0.00	0.00	96.00	96.00	96.00	96.00	96.00	96.00	96.00	96.00	96.00
CAN	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Dehaulming	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Fungicides	0.00	0.00	0.00	144.00	220.00	360.00	144.00	220.00	360.00	144.00	220.00	360.00
Seed transport	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Insecticides	24.00	24.00	24.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
Knapsack hire	0.00	0.00	0.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00
100 kg Bags	4.00	4.80	109.76	113.60	106.80	101.20	128.40	118.40	116.40	128.80	116.00	116.00
TVC	1794.07	1794.87	1899.83	2195.67	2264.87	2399.27	2210.47	2276.47	2414.47	2210.87	2274.07	2414.07
Gross profit	145.20	218.40	4018.67	4171.20	3920.40	3719.47	5984.53	5527.20	5437.60	4724.13	4253.33	4248.93
CBR	Loss	Loss	2.12	1.90	1.73	1.55	2.71	2.43	2.25	2.14	1.87	1.76
DNI				4026.00	3775.20	3574.27	5766.13	5308.80	5219.20	705.47	234.67	230.27
DIC				401.60	470.80	605.20	414.93	481.60	619.60	311.04	374.24	514.24
MRR				10.02	8.02	5.91	13.90	11.02	8.42	2.27	0.63	0.45

TVC CBR and DAP referred to total variable cost, cost benefit ratio and Diammonium phosphate respectively. Seed transport cost was per Km fungicide formulations, spray regime, rate of application and crop coverage can be affected by the literacy level of the farmer. In our study, the majority of the farmers received secondary education, which is sufficient for reading chemical application instructions as well as following advice from extension services. The effect of field size on late blight is another socio-demographic factor that can influence the efficacy of management methods. Small field sizes are possibly due to increasing land subdivision. The general increase in human population especially in the highland areas (most productive agricultural areas) coupled with urbanization (converting agricultural land to urban centers) could have contributed to the reduction in agricultural land size as observed by Maja and Ayano (2021). From our observations overtime, these small parcels of land prompt the farmers to continuously grow potato from season to season. This enhances survival and successes of *P. infestans* inoculum from one season to season. In addition, the efficiency of management practices can be reduced where the neighbour farmer delays or is unable to minimize late blight symptoms. This would result in transmission of the fungi widely throughout the cropping season. The choice of fungicide by the farmers was not clearly understood at the time of survey. For this reason we evaluated a number of fungicides used by the farmers to re-assess their efficacy on late blight management.

P. infestans thrives well when RH is high (above 95%) which is often influenced by rainfall aspects (Lal et al., 2018; Sparks et al., 2014; Hannukkala et al., 2007). Generally, increasing rainfall and RH provided conducive conditions for *P. infestans* proliferation. These results are in agreement with previous reports (Baker et al., 2015; Nærstad et al., 2007; Tiwari et al., 2021) which showed the significance of weather in the progression of late blight epidemics. However, we noted that disease progress 77 days after emergence coincided with low rainfall and declining RH below the 95% (RH) during the last phase of crop growth. This could be attributed to adaptability of the pathogen to local climatic conditions for survival as described by Janiszewska et al. (2021). Thus, occasional evaluation of the fungicides from the local markets on their efficacy in managing late blight is necessary to minimize emergence of fungicide insensitive strains and provide sustained disease control.

The use of fungicides influenced crop height and stem count in the Dutch Robjin (susceptible) and Shangi (moderate susceptible) varieties. Even though these characteristics are genetically controlled, it is evident that, the use of fungicides resulted in improved height growth, stem and hill count. The improved growth attributes could be associated with minimal late blight symptoms which is critical in enhancing optimal surface area for photosynthesis (Botero et al., 2018). These findings are further supported by the negative correlation ($r^2 = -0.75$) between late blight severity (AUDPC) and height growth observed in the present study. Similar observations were made by Bangemann et al. (2014) who found that, high foliar blight severity reduced crop growth by 52%. In addition, K. Mpya (resistant variety) height, stem and hill count in protected and unprotected plots were not significantly different, unlike in the Dutch Robjin and Shangi varieties which depended on fungicide application to minimize late blight effects. Apparently, reduced plant population (number of hills) observed in our study could pose detrimental effects on potato yield. Therefore, the study shows that, resistant varieties could be a useful tool in managing late blight in Kenya.

A number of studies have explored numerous strategies in managing the disease including, combinations of practices (integrated disease management) (Tadesse, 2019) and use of fungicides as sole effective approach (Majeed et al., 2017). In the present study, we evaluate the effectiveness of variety in combination with fungicide to manage late blight. We observed that the disease severity from the two sites (Tigoni and Njabini) was not significantly different despite the difference in weather conditions. This suggests that *P. infestans* has a wider adaptability to different weather regimes. In our study, it is evident that fungicides and variety played a pivotal role in managing late blight. While K. Mpya reduced the disease severity by more than 98% with no fungicide application, Dutch Robjin and Shangi required fungicides applications to reduce late blight severity. This is in agreement with Kirk et al. (2001), who reported that, susceptible varieties require multiple fungicide applications for effective late blight management throughout the cropping season. Performance of K. Mpya could be attributed to the R gene which might be absent in Dutch Robjin and Shangi (Paluchowska et al., 2022; Chen et al., 2017; Andrivon et al., 2006) Differences in fungicide formulation in managing late blight severity were revealed in this study. This indicates that, fungicide formulations differ in their efficacy to manage the disease, hence the need for re-evaluation to provide informed and precise recommendations. The phenomenon could be attributed to variation in co-formulation. Whilst, Mistress 72® has more quantities of systemic molecule (cymoxanil) than in Milraz® and contains mancozeb (curative) in the co-formulated fungicide, Milraz® has two preventive molecules (propineb). Thus, co-formulation of curative and preventive molecules seems to be effective on late blight. On the other hand, cymoxanil, seemed to work better than the other preventive molecules contained in the Ridomil® and infinito. Our results on performance of fungicides agree with Lal et al. (2015) who found that cymoxanil was more efficacious than metalaxyl when co-formulated with mancozeb to manage late blight. We recommend occasional evaluation of fungicide formulations and resistant varieties to monitor the occurrence of *P. infestans* genotypes variants.

In the present study, we report a strong positive correlation ($r^2 = 0.88$) between the stem count and the yield, and between height ($r^2 = 0.92$) and yield. This shows that any influence on optimal growth of the two crop attributes, would be reflected in yield loss. We report that, the effect of late blight on the two crop characteristics resulted in yield reduction. This is explicitly shown in the Dutch Robjin and Shangi varieties in the unprotected plots, compared with the protected plots. Even though, yield performance is genetical trait, our study suggests that late blight can reduce that capacity substantially. Higher yield and gross profit was observed when K. Mpya was planted with no fungicide applied. This is associated with the ability of K. Mpya to reduce late blight infection to below 2%. From our study, it is apparent that, the use of fungicides contributed to yield formation in both Shangi and Dutch Robjin. This could be linked to the efficacy of the fungicides in reducing late blight epidemics and their subsequent effects on the potato crop. The differences observed among chemicals in contributing to yield is associated with the differential capacity of the fungicides to manage late blight severity. Therefore, our study proposes that, fungicides cannot be avoided in managing late blight on susceptible varieties.

We observed that, K. Mpya variety had the highest return during the cropping season. This was attributed to the cost saving in chemical expenditures. On the other hand, unprotected plots of Dutch Robjin and Shangi resulted in loss owing to the detrimental effects of late blight on the varieties. In the plots in which fungicide was used, Shangi had the highest margin of return, followed by Dutch Robjin and then K. Mpya. Previous study by Kessel et al. (2018) also found that the use of resistant varieties could reduce use of fungicide by 90%. Notably, application of Mistress 72® resulted in a higher net benefit ratio and MRR than Ridomil® and infinito® in Shangi and Dutch Robjin. This is linked to the chemical consistency in reducing late blight symptoms as compared to other fungicides hence contributing to additional yield. In addition, Mistress 72® had a lower price than the other fungicides. We conclude that the use of effective fungicides is a usefull strategy for managing late blight in susceptible varieties. However, the resistance in K. Mpya can be a useful tool in managing late blight to minimize cost of production and other harmful effects associated with chemicals.

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Data availability The author agrees to avail data when required by the editor.

Declarations

Consent for publication Not applicable.

Competing interests The authors declare there is no conflict of interest in this manuscript.

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