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Effects of Seed Tuber Size of Potato Varieties on Fungicide Spray Regime, Weed Infestation and Net Farm Income in Potato Production

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Abstract
Field studies were conducted to determine the contribution of seed tuber size on late blight management, weed abundance, crop performance and net farm income. Seed tuber sizes were as follows: small size (15 to 27 mm), size 1 (28–35 mm), size 2 (36–45 mm) and size 3 (46–60 mm) of Shangi, Kenya Mpya, Unica and Dutch Robijn potato varieties. Fungicide spray regimes were weekly, biweekly and triweekly. Data on late blight severity, weed frequency and density, growth parameters, costs and revenues were collected. Results revealed that seed tuber size, variety and fungicide application regime had significant ($P \leq 0.05$) effects on late blight severity. As such, weekly spray intervals reduced blight severity by 50%, and the blight-tolerant variety (K. Mpya) suppressed the disease to below 1%. Whereas the lowest disease severity was observed on seed sizes 2 (44%) and 3 (43%), the highest blight score was recorded in small seed size (59%) after 70 days of emergence. Notwithstanding the variety used, a combination of seed size 2 with weekly spray interval showed the lowest disease progression as compared to any other combination. Crop growth parameters differences were phenomenal among seed sizes: stem count increased six-fold, while height and canopy were double the observation made in the small seed size for seed sizes 2 and 3. Weed frequency, relative frequency and density decreased with increasing seed size planted. As a result, seed tuber sizes 1, 2 and 3 augmented marketable yield by 49%, 62% and 65% as compared to the small tuber size, respectively. However, seed size 2 had the highest cost–benefit ratio (1.50), followed by size 3 (1.05).

Keywords Cost–benefit analysis · Late blight · Plant growth · Spray interval · Tuber size

Extended author information available on the last page of the article

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Introduction

Potato is an important food and income-generating crop globally, owing to its nutritional strength, high yield per unit area, wide adaptability in mid-to-high altitudes and early maturing attributes. The sub-sector employs over 2.5 million people directly and indirectly along the potato value chain (Mwakidoshi et al. 2021). Yet, in most sub-Saharan countries, potato farming faces a number of production constraints, including biotic and abiotic stresses. These challenges result in repressed yield, from the potential of 40 t ha^{-1} to between 8 and 10 t ha^{-1} (Muthoni et al. 2013). In Kenya, the seed system is characterised by both informal and formal structures. The most promising approach (formal seed system) supplies only about 5% of the total seed produced in the country (Schulte-Geldermann et al. 2012). Therefore, a high seed demand with respect to supply is apparent and remains a major drawback in the growing potato industry. In addition, the bulkiness of the potato seed increases transport and allied costs, besides the high cost of the seed. This has prompted the farmers, who majorly include smallholder growers, to use poor quality seed, including small-sized tubers, which are often regarded as economically inconsequential during harvesting (Muthoni and Nyamongo 2009). Cognizant of this and in efforts to promote food security, a number of countries have established measures to enhance improved potato production in the presence of already documented farming constraints (Andati et al. 2022). Among the key strategies is optimising plant health-associated practices at the earlier value chain phase, including the use of the right seed to improve on the perennial low yields (Finckh and Bruns 2006).

The inherent seed property is a fundamental resource in potato production. The outlays attributed to seed procurement take up to about 30% proportionate of the total cost of production (Rana et al. 2013). Thus, the need for selecting quality planting materials remains imperative. The quality of potato seed, as defined in this article as seed size and health, could be a useful tool in estimating expected yield during the decision-making process and budgeting. The size of the seed tuber informs on the number of stems expected to develop, and hence, the number of tubers harvested at the end of the cropping season can be estimated. Apparently, the larger the tuber seed size, the higher the number of eyes on the tuber. In line with this, there is a positive correlation between the number of eyes which develop into stems and yield (Asnake et al. 2023). Therefore, seed size is a physical primary indicator and measurable characteristic for seed quality, which often relates to harvest efficiency (Bussan et al. 2007; Wurr et al. 2001). Hence, the attribute is a useful factor for farm business planning and supporting decision-making processes (Demo et al. 2015).

Even though variations in tuber size could be attributed to genetic causes, environmental factors also play a significant role in influencing tuber size distribution at harvesting (Herman et al. 2016). The economic priority of each size may vary from seed to ware ventures. Seed size in Kenya is classified based on the diameter of the tuber as seed size 1 (28 to 35 mm), size 2 (36 to 45 mm) and size 3 (46 to 60 mm), according to Kenya Plant Health and Inspectorate Service

(KEPHIS) classification grading system of potato in Kenya. The choice of seed size often depends on farmers' level of capitation or experience. Most growers would prefer to purchase small-sized seeds, which will be more per bag to cover a comparatively larger area than bigger seed size, thus reducing the cost of production (Mumia et al. 2018). Yet, limited scientific data to prove implications on yield and net benefits attached exist to support pragmatic recommendations. Apparently, a higher number of stems and plant height, which directly relate to leaf area index (assimilation surface), contribute to the increased number of tubers per plant, dry matter concentration and root biomass. Moreover, seed size also influences seed emergence (bigger seed has more sprouts to increase the probability of emergence) and viability and increases survival of the sprouts (Diop et al. 2020).

Seed size also forms an important component in farm planning and budgeting. The quantity (number of bags per hectare) required to procure depends on the choice of seed size. In addition, potato seed is bulky, requiring transport and labour costs. From an experiential observation perspective, one hectare would require between 2.1 tonnes (size 1) to 2.5 tonnes (size 3). Thus, the size of the seed also influences the cost of production, specifically in terms of number of tubers required to plant in a given area. The challenge is that the seed is sold in terms of bags but not count. Therefore, the bigger-sized tubers will noticeably be fewer in a bag, hence requiring additional expenditure to purchase more bags in addition to extra transport costs. On the other hand, the bigger the tuber size, the higher the yield realised (Dimante et al. 2019). It remains unclear whether the additional yield could compensate for the lost revenue.

Often, the use of sizeable tuber size could result in strong sprouts (firmly attached) with high emergence and growth vigour, reducing possibilities of foliar disease infection and subsequent transmission to other neighbouring. Among the foliage-infecting diseases is late blight caused by *Phytophthora infestans*. The fungal disease is one of the most important diseases of potato. Yield losses attributed to late blight range from 70 to 100%, especially for susceptible varieties, if management measures are not applied and conditions conducive for the pathogen growth are prolonged (Kilonzi et al. 2022). A number of practices have been applied, including the use of biocontrols, fungicides (Kilonzi et al. 2020), cultural practices (Liljeroth et al. 2016) and resistance mechanisms (Tadesse 2019), yet the disease remains a major biotic challenge in potato production. The contribution of seed size to late blight management has, however, received less research interest. We hypothesise that seed size is responsible for providing seed thrust during emergence, high crop vigour and supporting the initial strong partitioning pathway. This often depends on the amount of reserves stored, which is a function of seed size. Expectedly, a large seed size provides sufficient nutrients and minerals, such as calcium, that could play a vital role in managing the disease. On the other hand, the high vegetative canopy can create a favourable microclimate (high relative humidity (96%), prolonged wetness on lower leaves (often not easily observed while scouting) and low temperature (< 18 °C), which promote late blight epidemics (Andrivon et al. 2011). The phenomenon remains unclear to most scientific community. The choice of variety also plays a critical role in managing late blight symptoms. Resistant varieties such as Kenya Mpya reduce weak symptomology effectively without the need to apply fungicides. On the other hand, susceptible varieties, including Dutch Robijn, would require weekly fungicide spray intervals to manage the disease (Kilonzi et al. 2022). Thus, there is a need to combine seed size, variety and fungicide application regimes to optimise efficacies in late blight management with minimal cost implications.

Growth vigour influences weed diversity and abundance. Indeed, a study conducted by Hermeziu et al. (2018) suggested that high growth vigour occurring early in the growing period (most critical stage) often stimulates emerging weed seedlings, thereby impacting their competitive edge. Moreover, it is worth noting that varietal dormancy attributes play a key role in crop emergence with respect to weed germination. As such, based on personal experiences, Unica and Dutch Robijn, which have a longer dormancy period of up to 6 and 2 months, respectively, affect weed infestation. Some farmers pre-sprout the seed to elude this, but pre-sprouting causes sprout breakages, resulting in stem count. If not pre-sprouted, the seed tuber takes a longer duration to emerge when planted, giving weeds the prospect to germinate and establish on the available space using nutrition supplied to the seed tuber. On the contrary, Shangi and Kenya Mpya sprout within two weeks without any supplementary efforts. This could then reduce the cost of production, increasing net farm returns for the farmer. Therefore, the findings of this study aim to contribute to knowledge useful to both the scientific community and potato growers on the role of seed size for improved production.

Materials and Methods

Study Site and Experimental Materials

The experiment was conducted during October to December 2021, short rain season and from April to July 2022, long rain season at KALRO Tigoni fields, Kiambu County. The centre lies at an altitude of 2300 m above sea level, latitude 10° 9´ 22˝ south and longitude 36° 4´ 72˝ east. The site experiences bimodal rainfall patterns with an average amount of 1800 mm per annum, while temperatures are in the range of 10 to 25 °C, respectively (Jaetzold et al. 2006).

Experimental Materials and Field Management

Four potato varieties of basic generational class, namely Unica, Dutch Robijn, Kenya Mpya and Shangi (Table 1) of size [small size (15 to 27 mm), size 1 (28 to 35 mm), size 2 (36 to 45 mm) and size 3 (46 to 60 mm)] were obtained from KALRO Tigoni. The land was prepared during dry periods, and planting was conducted at the onset of rains following farmers' practices. Diammonium phosphate (DAP) fertiliser was applied at a rate of 500 kg ha^{-1}. Late blight infection relied on natural infection. Ridomil® (metalaxyl 4 g + mancozeb 640 g) was procured from the local agrostokist and was used to protect the crop against late blight symptoms.

Table 1 Brief characteristics of varieties used in the experiment

Variety	Ecological requirements (m above sea level)	Yield potential (t ha^{-1})	Skin colour	Maturity (months)	Year of release	Blight susceptibility
Shangi	≥ 1500	30–40	White	≤ 3	2017	Moderately susceptible
K. Mpya	≥ 1500	≥ 40	White	3–4	2010	Tolerant
Dutch Robijn	1800–2600	≥ 30	Red	3.5–4.5	1960s	Susceptible
Unica	≥ 1200	≥ 45	Red	2.5–3.5	2015	Moderately susceptible

Source: NPCK potato catalogue, 2020

Experimental Designs

Field trials were laid side by side in which the first one pertained to observations on late blight severity, the second related to observation of weed abundance, and the last one assessed crop growth and yield attributes of potatoes. In the first experiment, fungicide spray regime (weekly, biweekly, triweekly), variety and seed size were the main plot, subplot and sub-subplot, respectively. These were laid in randomised complete block design in a split-plot arrangement with three replications. Control experiments included unsprayed plots, resistant variety (K. Mpya), susceptible variety (Dutch Robijn) and seed size 2 as standard size). In the second experiment, treatments were laid in two blocks separately for observation (weeded and unweeded plots). The treatments, namely varieties (Unica, Dutch Robijn, Kenya Mpya and Shangi) and seed size (small size, size 1, size 2 and size 3), were the main plot and sub-plot, respectively. Similarly, the third experiment included varieties and seed size in which variety and seed size were main plot and subplot, respectively. In the second and third experiments, the standard seed size (seed size 2) was the control, and the design used was a randomised complete block design in a split-plot arrangement with three replications. The experimental plot measured 3 × 3 m, and a spacing of 75 cm × 30 cm was adopted.

Estimating Weed Diversity

Weed abundance was determined through frequency (Eq. (1)), using 1 × 1 m quadrant (2 per quadrant per plot placed at the centre rows), while the number of species was established by physical counting per quadrant. Relative frequency (Eq. (2)) was used to determine species dispersion. Weed density was assessed using the number of each weed species observed per unit area.

$$\text{Frequency} = \frac{\text{Number of sampling units in which species occurred}}{\text{Total number of sampling units}} \times 100 \quad (1)$$

$$\text{Relative Frequency}(\%) = \frac{\text{Number of a species occurred}}{\text{Total number of all species}} \times 100 \quad (2)$$

Data Collection

Data on weather, mainly rainfall, was collected on a daily basis. Plant growth (height, stem count and canopy) measurements were taken 30 days, 45 days and 60 days after crop emergence. Late blight severity was recorded on a weekly basis starting from 21 days after emergence. Disease scoring was based on a scale of 1 to 10, where disease severity assessment was based on percentage of leaf area infected and interpreted into 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 the leaf area covered with blight symptoms (Andrivon et al. 2006). The weekly percentage of disease severity was used to calculate the area under the disease progress curve (AUDPC in %.days) at the end of each cropping season, as shown in Eq. (3) (Simko and Piepho 2012).

$$\text{AUDPC} = \sum_{\text{i}=1}^{\text{n}-1}\left(\frac{y_i + y_{i+1}}{2}\right)\text{x}\left(t_{i+1} - t_i\right) \tag{3}$$

where y_i, t_i, and ith represent an assessment of disease (percentage) at ith observation, time (days) at ith observation and ith represent the total number of observations, respectively.

Tubers were harvested from the inner rows and graded into chatt (< 28 mm), seed size (29 to 60 mm) and ware (> 61 mm) tuber grades. The tubers were weighed, and the yield was converted to tonnes per hectare before data analysis. Fresh weight (foliage and roots separately) was obtained from randomly selected crops and recorded before placing them in an oven at 80 °C overnight. Then, dry weight was recorded, and root-to-whole crop dry matter was calculated. At physiological maturity, tubers were sampled from 2 hills from exterior rows, washed using distilled water and air dried. Fresh weight was determined using a weighing scale. The root biomass index was determined (Eq. (4)).

$$\text{Root Biomass Index} = \frac{\text{Dry weight of roots}}{\text{Dry weight of whole plant}} \times 100 \tag{4}$$

Costs and Benefits

Costs and revenues (means of the two seasons) that did not apply uniformly to all treatments were recorded for cost–benefit analysis. Partial budgeting was conducted using marginal rate of return and net benefit analysis (Eq. (5)). Treatment or treatment combinations which gave the highest marginal rate of return percentage were classified as the most economical alternative. Moreover, gross margin analysis was conducted to measure the economic efficiency of each technology adopted.

To compare seed treatment methods and seed type costs and benefits, the ratio of the net benefits (Gross margin) to total variable costs was calculated. Treatment that showed the highest ratio was regarded as more economical.

$$\text{Cost Benefit ratio} = \frac{\text{Net benefit}}{\text{Total variable costs}} \tag{5}$$

Data Analysis

Analysis of variance was calculated to determine the effect of fungicides, varieties, seed size and their combined effect on late blight and contribution to yield. All statistical analyses were conducted using SAS software, and treatment means were compared using Tukey's honest significant difference ($p \leq 0.05$). Standard error was used to compare the means of treatments' interactions.

Results

Rainfall Amount During the Cropping Season

Rainfall is the single most important environmental factor in any crop production, and therefore, its observation was critical in this study. During the two cropping seasons, short rain season generally had a higher rainfall amount on average as compared to long rain season. However, the highest amount (280 mm) was observed after 42 days of crop emergence in the long rain season, followed by about 250 mm in the short rain season (14 days after emergence). It is worth noting that, in both cropping seasons, rainfall was received on a weekly basis, which provided favourable conditions for *P. infestans* growth and development (Fig. 1).

Late Blight Symptomatology

Effects of variety on late blight symptoms development were significant ($P \leq 0.05$) during the cropping seasons. Kenya Mpya consistently suppressed symptoms of the disease to below 1% during the cropping season (Fig. 2). On the other hand, Dutch Robijn had the highest late blight severity of about 60%, followed by Shangi (50%) and Unica (40%) by the end of the cropping seasons (Fig. 2). Fungicide application regime also had significant contribution in managing late blight. Expectedly, weekly spray application interval showed the least disease severity, followed by biweekly and triweekly in that order from 42 to 70 days after crop emergence. Whereas, weekly spray interval reduced AUPDC by 50%, and biweekly and triweekly suppressed the disease by 42% and 31%, respectively (Table 2). It was observed that the size of the seed tuber contributed to the management of late blight during both growing periods. The smallest tuber size had the highest disease score, followed by

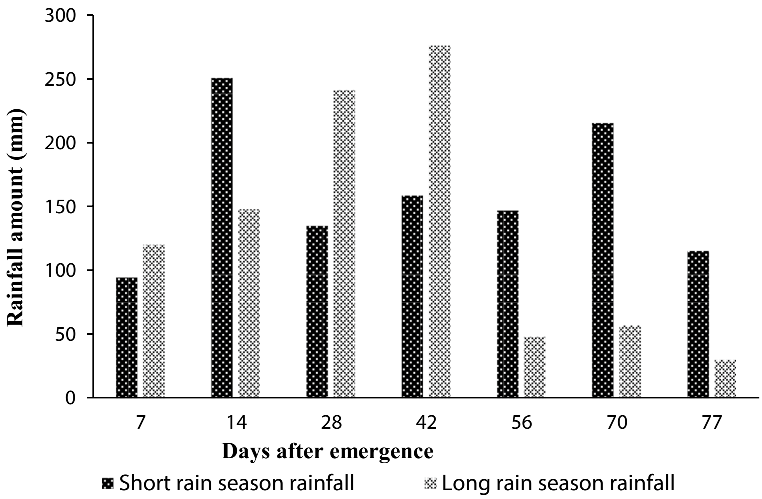

Fig. 1 Rainfall amount recorded across days after emergence during long and short rain seasons

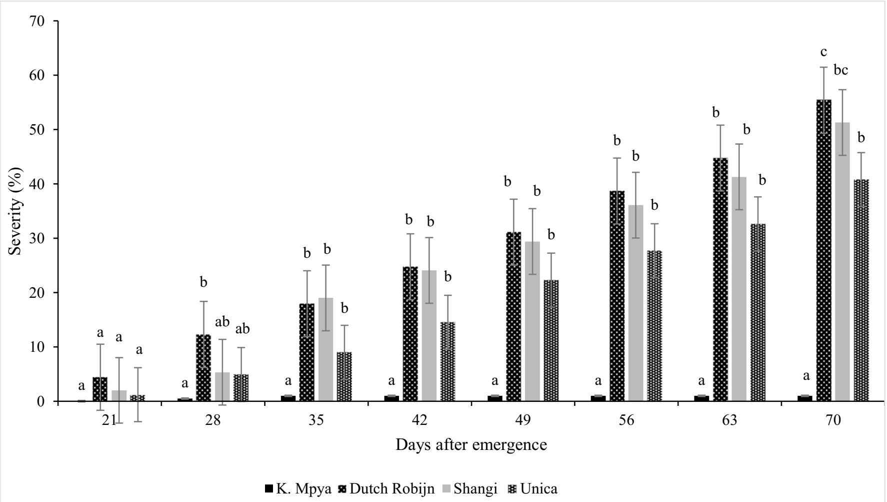

Fig. 2 Effects of variety on late blight severity observed across days of potato crop emergence in the unsprayed plots

seed size 1, while seed sizes 2 and 3 were not significantly different ($P \leq 0.05$). The smallest tuber sizes had higher disease (59%), while seed sizes 2 and 3, which were not significantly different, had the lowest score (Table 3). Notably, seed sizes 2 and 3 repressed blight AUDPC by 26% and 29%, respectively. Figure 3a suggests that, in general, the unprotected plot had the highest disease severity in all tuber sizes. Small seed size and seed size 1 required weekly spray intervals to minimise late blight severity, while seed sizes 2 and 3 required a delay of up to three weeks to apply fungicide. The figure further shows that the interaction between the seed tuber size and weekly fungicide spray showed substantial suppression of late blight severity. In Fig. 3b, it was apparent that the application of fungicides at weekly intervals played a vital on managing late blight on the susceptible varieties.

Table 2 Effects of fungicide spray regime on late blight severity percentage across days after emergence and AUDPC

Regime	Late blight severity (%) across days after emergence (DAE)								AUDPC (%.days)
	21	28	35	42	49	56	63	70	
Weekly	2.03a	6.36a	12.00a	13.47a	19.67a	27.06a	30.99a	39.67a	1030a
Biweekly	2.39a	6.83a	13.83ab	18.72b	24.22b	30.25ab	35.44ab	45.19ab	1229 a
Triweekly	2.92a	7.78a	15.42b	22.03c	28.11c	33.28b	38.86b	49.17b	1423b
Control	2.83a	7.08a	22.08c	30.28d	38.42d	46.06c	52.97c	62.89c	2067c
$HSD_{0.05}$	0.48	1.01	1.93	1.97	2.05	2.52	3.30	3.33	117.20
CV%	30.67	21.87	20.45	15.15	12.09	12.02	13.57	10.99	13.26
Mean	2.54	7.51	15.33	21.13	27.60	34.16	39.56	49.23	1438

A number followed by a similar letter within the same column indicates that the treatments do not differ significantly

Table 3 Effects of seed size on late blight severity percentage and AUDPC (means)

Seed size	Late blight severity across DAE (%)								AUDPC (%.days)
	21	28	35	42	49	56	63	70	
46–60 mm	1.78a	5.42a	11.08a	16.72a	22.72a	29.42a	35.36a	42.56a	1226a
36–45 mm	1.86a	5.89a	11.33a	16.75a	24.44a	30.75a	36.92a	44.01a	1291a
28–35 mm	2.69a	8.14b	16.33b	22.50b	28.36b	35.72b	41.25b	52.00b	1496b
15–27 mm	3.83b	10.61c	22.58c	28.53c	34.89c	40.69b	44.64b	58.81c	1738c
$HSD_{0.05}$	0.48	1.01	1.93	1.97	2.05	2.52	3.30	3.33	117.20
CV%	30.67	21.87	20.45	15.15	12.09	12.02	13.57	10.99	13.26

A number followed by a similar letter within the same column indicates that the treatments do not differ significantly

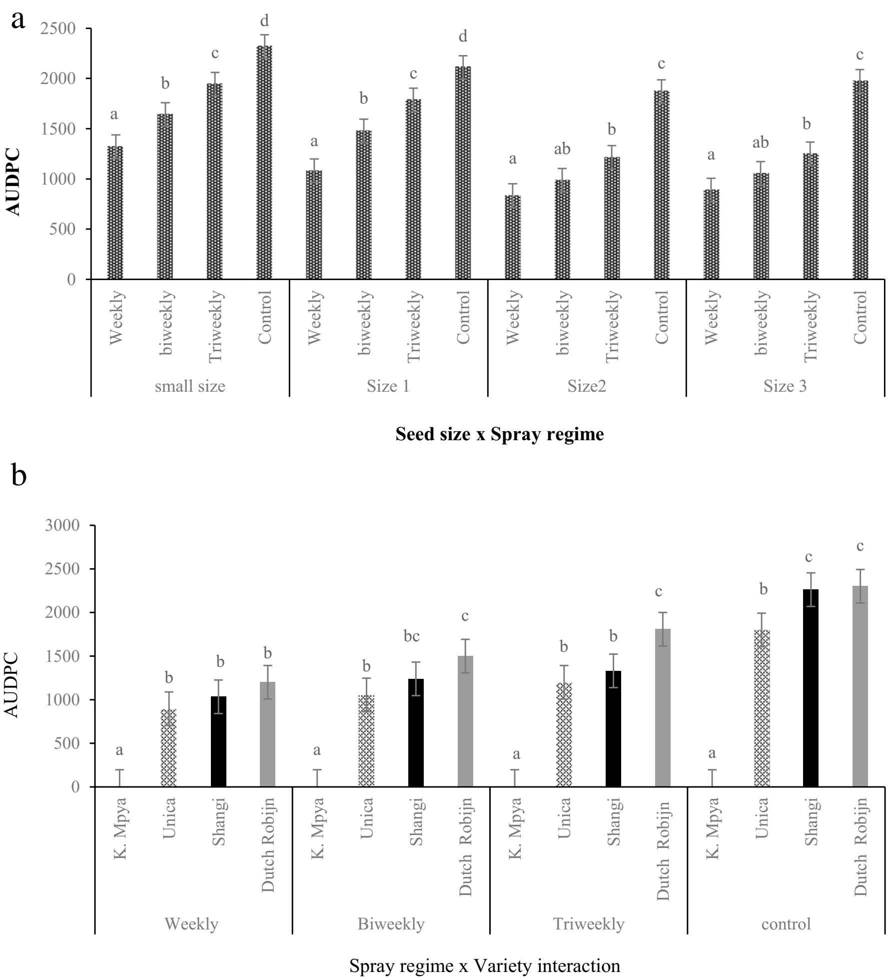

Fig. 3 Effects of seed tuber size and fungicide spray regime on late blight area under disease progress curve. **b** Effects of spray regime interaction with variety on AUDPC. AUDPC is expressed in %.days

Effects of Seed Tuber Size and Variety on Weed Abundance

Weed species observed during the cropping season in the unprotected plots are presented in Table 4. Only annual weeds were observed in which Mexican marigold, gallant soldier and cornyza were the most dominant-based frequency parameters. Data on weed frequency and relative frequency suggested that the larger the seed, the less the data observed with a uniform trajectory, alluding that higher weed abundance was observed in the small seed size (Table 4). Furthermore, the correlation between the seed size and weed species population showed a strong negative correlation of −96% during the cropping seasons (Fig. 4). In the unweeded plot, Unica had the highest density values for the majority of weeds, followed by Dutch Robijn, while Shangi and K. Mpya had the lowest values. Only wild radish infestation had no significant difference among the varieties (Fig. 5).

Effects of Seed Tuber Size, Variety and Their Interactions on Stem Count, Height and Canopy Growth Attributes in the Weeded Plots

Data on emergence showed that tuber seed size and potato variety both influenced plant population during the cropping season. Notably, within the first 14 days after planting, emergence increased with increasing seed size, which had a positive correlation of 75% (Fig. 6a). The highest crop growth gradient was observed within 45 DAE. Similarly, data on growth had a similar trend as emergence. Higher height increase aptitude was manifested in seed sizes 2 and 3, reaching a maximum height of about 78 cm as compared to small size seed and seed size 1 that recorded 40 cm and 45 cm, respectively (Fig. 6b). Stem count suggested that small size showed the least rate of increase during the cropping season, followed by seed size 1 (Fig. 6c). All seed sizes showed higher canopy growth gradient within the 45 DAE, yet seed size 3 and 2 attained the highest recorded measurement by the end of 60 DAE (Fig. 6d). Unica showed the least emergence (90%) within the first 14 days of observation, followed by Dutch Robijn (96%), while Shangi and K. Mpya which had the highest emergence were not significantly different ($p \leq 0.05$). However, Unica had the highest canopy measurement as compared to the three varieties, with the Dutch Robijn having the lowest. Stem count did not differ significantly among the varieties. While Dutch Robijn had the lowest height measurement, Shangi, K. Mpya and Unica had the highest and were not significantly different (Table 5). On the other hand, the interaction between seed size and variety showed that only seed sizes 2 and 3 had the same emergence data.

Effects of Seed Tuber Size, Variety and Their Interaction on Yield Parameters in the Weeded Plots

Results suggest that selecting a bigger seed to plant would result in higher yield and yield components. Indeed, there was a strong positive correlation between tuber seed size and foliage dry matter (DM) (0.78) (Fig. 7a). Similarly, a positive correlation of 0.81 between seed size and roots DM was also observed

Table 4 Effects of seed tuber size on weed abundance from unweeded plot

Common name	Scientific name	Weed Frequency				Weed Relative frequency			
		Small size	Size 1	Size 2	Size 3	Small size	Size 1	Size 2	Size 3
Wild radish	*Raphanus raphnistrum*	62.5	62.5	37.5	25.0	9.29	8.53	7.87	7.15
Black jack	*Bidens pilosa*	75.0	50.0	25.0	12.5	13.09	12.73	9.42	8.41
Couch grass	*Cynodon dactylon*	62.5	62.5	37.5	25.0	5.78	6.07	3.69	2.88
Kikuyu grass	*Pennisetum clandestinum*	37.5	25.0	25.0	12.5	2.80	2.43	0.53	0.36
Portulaca	*Portulaca oleracea*	62.5	50.0	25.0	25.0	1.92	1.39	1.06	1.44
Amaranthus	*Amaranthus sp.*	100.0	100.0	75.0	37.5	7.98	7.11	7.39	4.32
Double thorn	*Rumex hypogaeus*	100.0	62.5	37.5	37.5	0.72	0.57	0.53	0.53
Mexican merigold	*Tagetes minuta*	100.0	100.0	88.2	62.5	29.23	26.34	22.69	22.90
Wondering jew	*Tradescantia zebrina*	37.5	37.5	25.0	25.0	0.80	0.53	0.46	0.35
Oxalis	*Oxalis violacea*	37.5	100.0	75.0	50.0	1.38	1.21	0.79	0.68
Gallant soldier	*Galinsaga parriflo*	100.0	100.0	87.5	62.5	14.44	13.29	9.37	9.14
Chinese lantern	*Physali angulata*	100.0	100.0	75.0	50.0	8.90	9.88	6.33	6.12
Cornyza	*Erigeron canadensis*	100.0	100.0	75.0	50.0	4.15	3.99	2.90	2.88

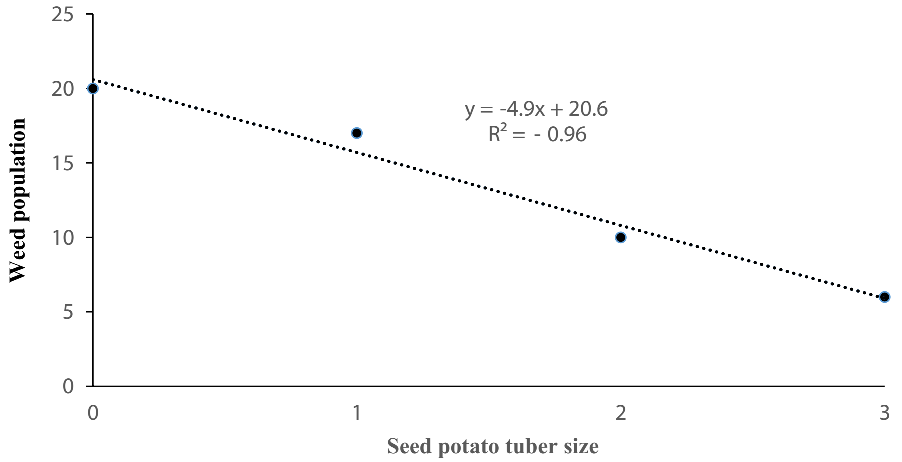

Fig. 4 The correlation between seed size and weed population observed in unprotected plots

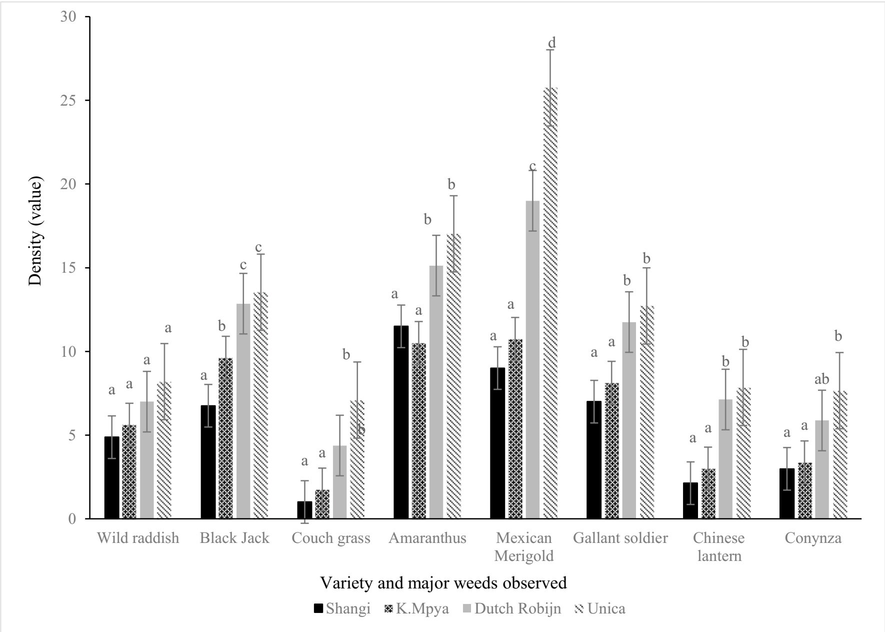

Fig. 5 Effects of seed tuber size on weed density of major weeds from the unweeded plots

(Fig. 7b). Furthermore, seed size 2 and 3 were not significantly different and had the highest root biomass index. It was observed that chatt grade weight was not significantly different among the seed grades, but seed grade weight data showed that small seed size had the least yield, followed by seed size 1. Increasing seed size from small size seed to seed size 3 resulted in significantly higher yield

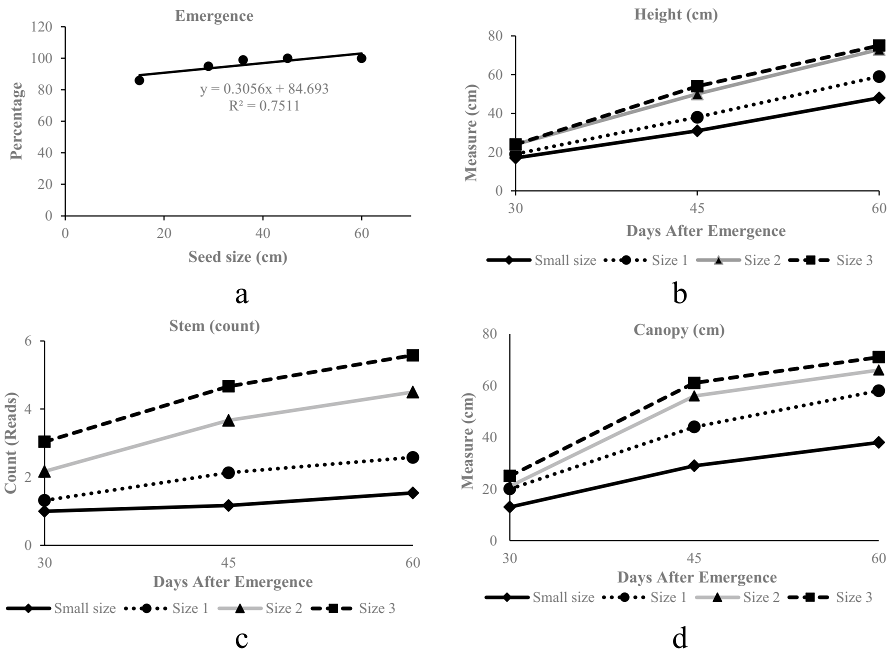

Fig. 6 Effects of tuber size on emergence (**a**), height (**b**), stem count (**c**) and canopy (**d**) measurement across days after emergence

(Table 6). On the other hand, in general, while Unica had the highest yield and yield components, Dutch Robijn had the lowest data. Dry matter of foliage and roots was higher in Unica than in the other three varieties. Even though chatt and seed weight were not significantly different among the varieties, ware weight, marketable and total yield differed among the varieties (Table 7). The interaction between seed size and variety is presented in Table 8. Briefly, the performance of the seed sizes of Shangi, Unica and K. Mpya varieties, in terms of yield, were the same. Remarkebly, seed size 3 of the four varieties had the highest seed and ware grade count and highest yield in terms of ware grade weight, marketable and total yield as compared to other seed sizes. However, in terms of tubers per hill, root biomass index, DM and seed grade weight, seed size 3 was not significantly different ($p \leq 0.05$) from seed size 2. Notably, seed size 1 had the highest chatt count and chatt weight. The lowest yield was observed in the small seed size. A similar performance trajectory was observed in Dutch Robijn with the exception of chatt and ware weight grade, in which seed sizes 2 and 3 did not differ significantly.

Profitability Analysis

The cost of seed was KES 3200 per 50 kg bag. The number of bags required to plant a hectare varied as per seed size. The cost of weeding and spraying one hectare was

Table 5 Effects of variety on emergence after 14 days of emergence and height, stem and canopy growth across days after emergence

Variety	Emergence (%)	Height (cm) taken across DAE			Stem (count) taken across DAE			Canopy (cm) taken across DAE		
		30 DAE	45 DAE	60 DAE	30 DAE	45 DAE	60 DAE	30 DAE	45 DAE	60 DAE
Dutch Robijn	95.92b	14.59a	36.37a	50.29a	1.58a	2.70a	3.58a	18.69a	45.90a	51.87a
K. Mpya	98.75b	21.73b	42.36b	67.93b	1.96a	2.96a	3.38a	21.46a	50.76c	58.38b
Shangi	99.25b	25.29c	51.53c	69.34b	2.11a	3.08a	3.84a	20.01a	40.68b	59.67b
Unica	90.17a	22.62bc	42.78b	67.48b	1.86a	2.86a	3.71a	18.86a	52.28d	62.59c
HSD	1.93	1.48	1.71	1.71	0.28	0.48	0.67	2.00	1.39	1.38
CV%	2.69	9.27	5.20	3.90	19.00	21.62	25.04	13.38	3.87	3.14

A number followed by the same letter in the same column indicates the treatments do not differ significantly

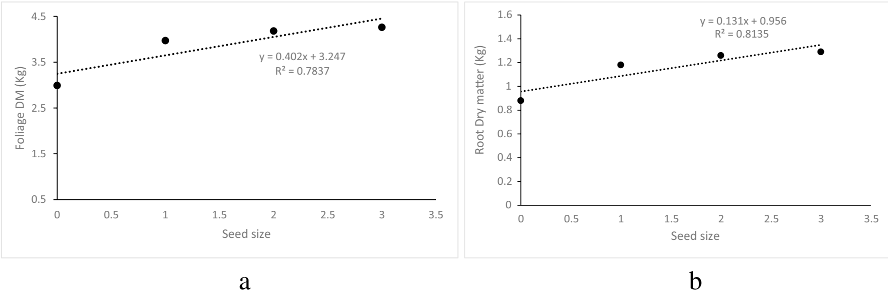

Fig. 7 Correlation between seed size and foliage (**a**) and roots dry matter (**b**)

Table 6 Effects of seed size on yield parameters

Seed size	Root biomass index (%)	Chatt (t ha^{-1})	Seed (t ha^{-1})	Ware (t ha^{-1})	Marketable yield (t ha^{-1})	Total yield (t ha^{-1})
Small size	20.66a	1.36a	6.13a	3.53a	9.65a	11.01a
Size 1	22.92ab	1.57a	11.19b	8.90b	20.09b	21.60b
Size 2	23.17b	1.12a	13.09c	11.81c	24.90c	26.02c
Size 3	23.18b	1.04a	13.84c	13.81d	27.65d	28.69d
HSD	0.38	0.24	1.05	1.17	0.73	0.71
CV(%)	2.19	24.93	12.58	16.18	4.71	4.30

A number followed by the same letter in the same column indicates the treatments do not differ significantly

KES 4800 and KES 600, respectively, during the cropping seasons. The small seed size and seed size 1 required a weekly spray regime (8 times a cropping season), while seeds 2 and 3 required biweekly spray (4 times a cropping season). It cost KES 100 to hire a knapsack to apply fungicide (Ridomil®) on one hectare, and the cost of the Ridomil® was KES 2000 per kg applied at a rate of 2.5 kg ha^{-1}. An extra weeding (3 weedings) activity was required for seed size 1 and the small size to reduce the weed population. Seed transport was estimated at KES 60 per km t^{-1} based on information collected from transporters in Limuru. The average price of a 100 kg bag of ware potato was KES 2500 during the harvesting period in both seasons.

Even though the use of seed size 3 gave 9.30% higher gross profit than seed size 2, the latter had the highest cost–benefit ratio of 1.50. The cost of seed had the highest proportionate of the cost of production in the partial budgeting, especially for seed size 3. The small seed size grade had the least revenue, lowest total value cost and net profit. The number of bags of seed was lower for seed size 1 and small size resulting in lower cost of seed and seed transport. The cost of protecting seed size 1 and small size against late blight was double the cost observed for seed sizes 2 and 3 (Table 9).

Table 7 Effects of variety on yield parameters

Variety	Foliage DM	Root DM	Root biomass index (%)	Chatt (t ha^{-1})	Seed (t ha^{-1})	Ware (t ha^{-1})	Marketable yield (t ha^{-1})	Total (t ha^{-1})
Dutch Robijn	367.39a	102.47a	21.43a	1.34a	10.74a	8.20a	18.93a	20.28a
Shangi	388.66b	114.54b	23.28c	1.12a	11.68a	9.92b	20.60c	21.73b
K. Mpya	390.47c	127.94c	24.53d	1.49a	11.18a	8.56a	19.74b	21.23b
Unica	402.87d	138.89d	22.58b	1.07a	11.65a	11.37c	23.01d	24.08c
HSD	3.28	2.26	0.38	0.24	1.05	1.17	0.73	0.71
CV(%)	1.12	2.58	2.19	24.93	12.58	16.18	4.71	4.30

A number followed by the same letter in the same column indicates the treatments do not differ significantly

Table 8 Effects of interaction between variety by seed tuber size on yield and yield components

Variety	Seed size (mm)	Chatt count per hill	Chatt wt (t/ha)	Seed count per hill	Seed wt (t/ha)	Ware count per hill	Ware wt (t/ha)	DM (kg ha^{-1})	Root biomass index (%)	Tubers/hill	Marketable yield (t/ha)	Total yield (t/ha)
Shangi	15 to 27	3.14 ± 0.30c	1.19 ± 0.12bc	1.19 ± 0.04a	5.32 ± 0.35b	0.67 ± 0.11a	4.57 ± 0.37a	381 ± 6.75a	17.94 ± 0.46a	5.00 ± 0.14a	9.89 ± 0.15a	11.07 ± 0.13a
	28 to 35	3.83 ± 0.18d	1.35 ± 0.07c	2.55 ± 0.29b	10.10 ± 0.12a	1.33 ± 0.17b	9.25 ± 0.25b	486 ± 5.98b	20.61 ± 0.25b	7.72 ± 0.43b	19.34 ± 0.25b	20.67 ± 0.28b
	36 to 45	2.79 ± 0.20b	1.05 ± 0.06b	3.25 ± 0.17c	13.36 ± 0.40c	2.38 ± 0.17c	11.42 ± 0.34c	529 ± 7.69c	20.59 ± 0.37b	8.42 ± 0.21c	24.78 ± 0.50c	25.83 ± 0.48c
	46 to 60	1.88 ± 0.20a	0.90 ± 0.06a	4.21 ± 0.35d	13.96 ± 0.79c	3.46 ± 0.12d	14.45 ± 0.77d	535 ± 6.14c	20.40 ± 0.26b	9.54 ± 0.29c	28.41 ± 0.31d	29.31 ± 0.32d
Dutch Robijn	15 to 27	2.67 ± 0.23ab	1.54 ± 0.15a	1.42 ± 0.11a	4.64 ± 0.42a	0.92 ± 0.08a	4.52 ± 0.58a	355 ± 11.24a	20.08 ± 0.63a	5.0 ± 0.27a	9.16 ± 0.27a	10.71 ± 0.14a
	28 to 35	3.50 ± 0.01c	1.74 ± 0.24a	2.63 ± 0.09b	11.23 ± 0.49b	1.13 ± 0.21b	7.21 ± 0.65b	508 ± 6.00b	24.53 ± 0.29b	7.25 ± 0.22b	18.44 ± 0.55b	20.18 ± 0.58b
	36 to 45	2.90 ± 0.13b	1.15 ± 0.10a	3.33 ± 0.23c	12.51 ± 0.32b	1.92 ± 0.12c	10.31 ± 0.40c	527 ± 5.92c	24.42 ± 0.19b	8.15 ± 0.16c	22.82 ± 0.21c	23.96 ± 0.25c
	46 to 60	2.04 ± 0.60a	0.94 ± 0.17a	4.06 ± 0.28d	14.57 ± 0.72c	2.33 ± 0.36d	10.74 ± 0.36c	536 ± 5.17c	24.72 ± 0.22b	8.43 ± 0.42c	25.31 ± 0.28d	26.25 ± 0.23d
Unica	15 to 27	3.40 ± 0.50c	1.04 ± 0.19a	1.30 ± 0.15a	6.86 ± 1.00a	0.58 ± 0.19a	3.12 ± 1.16a	397 ± 4.47a	19.97 ± 0.29a	4.28 ± 0.39a	9.98 ± 0.56a	11.02 ± 0.47a
	28 to 35	2.63 ± 0.33b	1.16 ± 0.22a	2.07 ± 0.15b	11.75 ± 0.57b	1.44 ± 0.36b	11.71 ± 0.34b	532 ± 6.64b	22.15 ± 0.30b	6.13 ± 0.57b	23.46 ± 0.73b	24.62 ± 0.77b
	36 to 45	1.96 ± 0.08a	0.85 ± 0.06a	3.73 ± 0.30c	13.80 ± 0.26c	3.12 ± 0.22c	14.17 ± 0.31c	566 ± 6.92c	22.13 ± 0.30b	8.21 ± 0.41c	27.97 ± 0.18c	28.85 ± 0.19c
	46 to 60	1.82 ± 0.28a	1.20 ± 0.19a	3.81 ± 0.22c	14.18 ± 0.21c	3.78 ± 0.39d	16.46 ± 0.17d	582 ± 6.42c	22.10 ± 0.21b	8.33 ± 0.41c	30.65 ± 0.25d	31.84 ± 0.24d
K. Mpya	15 to 27	3.00 ± 0.20d	1.67 ± 0.08c	1.46 ± 0.16a	7.69 ± 0.49a	0.42 ± 0.14a	1.90 ± 0.68a	415 ± 5.72a	22.67 ± 0.56a	4.88 ± 0.30a	9.59 ± 0.31a	11.26 ± 0.26a
	28 to 35	3.46 ± 0.15c	1.80 ± 0.22c	2.33 ± 0.27b	11.67 ± 1.37b	0.96 ± 0.20b	7.44 ± 1.52b	534 ± 5.88b	24.40 ± 0.23b	6.75 ± 0.24b	19.11 ± 0.48b	20.91 ± 0.63b
	36 to 45	2.42 ± 0.14b	1.38 ± 0.10b	3.54 ± 0.18c	12.78 ± 0.39c	2.92 ± 0.08c	11.35 ± 0.31c	557 ± 3.94c	25.59 ± 0.24b	8.88 ± 0.29c	24.05 ± 0.47c	25.43 ± 0.44c
	46 to 60	1.92 ± 0.12a	1.12 ± 0.06a	3.96 ± 0.10d	12.66 ± 0.43c	3.25 ± 0.27d	13.57 ± 0.45d	568 ± 4.20c	25.47 ± 0.15b	9.13 ± 0.29c	26.23 ± 0.10d	27.35 ± 0.10d
CV%		17.51	24.93	18.01	12.58	25.26	16.18	1.25	2.19	9.75	4.71	4.31

A number followed by the same letter in the same column indicates the treatments do not differ significantly. Wt represents weight

Table 9 Cost–benefit analysis on the effect of seed tuber size on farm returns using average yield in hectare

Seed size/input	Yield (t ha^{-1})	Adjusted yield s(t ha^{-1})	Revenue (KES)	Seed (bags)	Seed costs (KES)	Seed transport (KES per km)	Fungi-cide cost (KES)	Knap-sack hire (KES)	Weeding labour (KES)	Spraying labour (KES)	**Total value cost** (KES)	**Gross profit** (KES)	**Net profit** (KES)	**CBR**
Small size	11.01	9.91	247,750	32	102,400	96	40,000	800	14,400	4,800	162,496	247,750	85,254	0.52
Size 1	21.60	19.44	486,000	44	140,800	132	40,000	800	14,400	4,800	200,932	486,000	285,068	1.42
Size 2	26.02	23.42	585,500	63	201,600	189	20,000	400	9,600	2,400	234,189	585,500	351,311	1.50
Size3	28.69	25.82	645,500	88	281,600	264	20,000	400	9,600	2,400	314,264	645,500	331,236	1.05

CBR, cost–benefit ratio

Discussion

The symptoms of late blight progression are influenced by the inherent genetic potential of potato variety, environmental conditions, pathogen virulence and crop management practices applied by growers. The disease is majorly managed by the use of fungicides which often pose economic (Baćmaga et al. 2016), environmental and human health concerns (Kilonzi et al. 2021). Thus, crop resistance could be utilised to develop a more sustainable practice in managing biotic stress. Unfortunately, the strategy is not sufficient over time as incidences of *R*-gene collapsing have been reported in potato-producing regions globally (Paluchowska et al. 2022) and thus compelling availing breeding system strategies following the emergence of the more virulent and aggressive *P. infestans* strains.

From the present study, K. Mpya, a resistant variety of Kenya, released in 2010, showed consistent tolerance to late blight over the years. This could be attributed to either the variety *R*-gene being effective against vertifolia effects or, in Kenya, the emergence of a new virulent strain of the pathogen able to counter the activities of the *R*-gene is non-existent. Thus, this study concludes that the application of fungicides on K. Mpya is not required. On the contrary, farmers' preference for variety choice influences their production in Kenya. The effects of late blight severity were substantive on the moderate susceptible (Unica) and susceptible varieties (Dutch Robijn and Shangi). Therefore, the application of fungicide to manage blight on these varieties was significant during the cropping season but with different aptitudes. A weekly fungicide application regime was more effective when applied on the susceptible varieties than biweekly and triweekly. Moreover, our study suggested that the choice of seed tuber size played a key role in contributing to the management of late blight symptomatology. Of significance, higher disease severity was recorded in the plots in which the smallest seed size and seed size 1 were planted. This could be a result of vigorous growth conveyed by seed sizes 2 and 3 occurring early in the growth phase, promoting efficient partitioning at initial vegetative stages. This enabled avoidance/escape of early disease infections, a growing phase in which the potato leaves are tender and hence more vulnerable (Fulladolsa et al. 2018). Furthermore, larger seed provides more nutritive support for the young emerging crop, some of which are essential in plant defence systems. Previous studies showed that calcium and potassium are essential in maintaining the integrity of the cell membrane and thereby reducing the possibilities of the host plant-pathogen interaction (Ghorbani et al. 2008).

Apparently, larger tuber sizes had the highest emergence, which translated to a higher plant population (harvestable hills) at harvesting. By virtue of having a higher number of eyes (sprouts), the probability of earlier emergence as compared to the small tuber size that had about 2–3 eyes is phenomenal. A study conducted by Bussan et al. (2007) suggested that the bigger the tuber size, the higher the emergence results. The large seed tubers provide sufficient food materials that offer the growing plant with a vigorous thrust above the ground (Clark and Burge 2000). Similarly, it was observed that increasing tuber size from 15 to about 60 mm resulted in an increase in growth vigour by more than two-fold during the cropping seasons. Crop height and canopy doubled when seed tuber size 3 was used, while stem count increased six times relative to the small seed size. The proponent that the bigger the tuber size, the higher the amount of food reserve to support the young growing crop was evident. This study is in agreement with previous work that revealed a similar trajectory and that there is a strong correlation between the tuber size and the number of stems (Dimante and Gaile 2018). (Singh et al. 2020). In terms of growth, Unica and Shangi reached maturity earlier than Dutch Robijn and K. Mpya, owing to their genetic makeup in dormancy attributes.

Weeds form an important component of agroecosystems but present trade-offs in their role in biodiversity and as a key component in plummeting crop yield (Harker and O'Donovan 2013). Weed infestation and their successes in potato fields often depend on available farming practices and the stage of the crop. For instance, the present study showed that annual weeds were prevalent during the two cropping seasons as a result of continuous cultivation. Additionally, seed sizes 2 and 3 were able to subdue a number of weed species and abundance as compared to seed size 1 and the smallest tuber size. Vigorous growth observed in seed sizes 2 and 3 often leads to increased foliage coverage at a faster rate, competing for space, light and nutrients against weeds. Damage attributed to weeds in potato fields may be severe and diverse and could be influenced by microclimate as a result of crop canopy growth (Shehata et al. 2019). Varieties' growth habits also play a critical role in managing weed growth and infestation. For instance, in our study, Unica (with long dormancy) showed a long emergence period which allowed weeds to grow, providing a vast competitive edge to foster vigorous growth early in the growing period. The ultimate effects were apparent in unweeded plots in which Unica was planted.

Even though Nolte et al. (2003) reported that seed size did not substantially affect the total yield of potatoes in their investigation, our study and in agreement with Arsenault and Christie (2004) study found that seed size influences the growth vigour of potatoes, consequently implicating on yield. In addition, the yield of potatoes can be predicted by the number of tubers per plant at harvesting as well as population per unit area (Struik and Lommen 1999), and therefore, any factor influencing these components would result in lower yield. Noteworthy, yield is a genetically and environmentally controlled aspect in potato varieties, but crop management also influences varietal performance (Sadawarti et al. 2018). Of the factors in crop management, seed size is one of the controllable factors that could be manipulated to enhance higher yields. The present study was in tandem with the proponent that the choice of seed tuber size significantly influences the yield and yield component. Increasing seed size from 15 to 60 mm resulted in increased yield by more than two-fold. The findings are also in agreement with Haverkort and Verhagen (2008), who reported that an increase in seed size contributed to a substantial increase in yield and yield component qualities. Generally, from the varieties under investigation, a higher number of tubers and a higher number of marketable sizes were observed from plots in which seed size 3 was planted. On the other hand, seed size 2 gave uniform tuber size distribution as compared to seed size 3, which mainly had ware grade contrary to the findings reported by Fulladolsa et al. (2018). The combinations of events associated with growth and stem count following increased partitioning could have contributed to the additional yield. This study, therefore, affirms that seed size is an important consideration in potato production. Similarly, proponents were proposed by Haverkort and Verhagen (2008). In terms of varietal performance, Unica had the highest yield, followed by Shangi. K. Mpya and Dutch Robijn in that order. This could be attributed to the inherent genetic potential of the genotypes to have differential yielding ability despite the contribution of the environment (Radouani and Lauer 2015). Whereas the highest gross profit was observed in seed size 3, the highest net benefit and cost–benefit ratio were observed in seed size 2, followed by seed size 1. The course is attributed to higher seed cost and seed transport that surpassed additional yield generated by the seed size 3, resulting in lower net benefit. Based on our findings, the use of seed size 2 is recommended as it provides higher net farm returns. However, when selecting a variety, appropriate spray regime needs to be observed depending on the variety susceptibility to blight as well weed management.

Conclusions

Kenya Mpya variety reduced late blight severity by up to 100%. Weekly spray intervals provided the highest level of protection against late blight as compared to other regimes. Seed size had a significant contribution to crop growth, blight infection, weed management, dry matter, number of tubers per hill, seed distribution and yield formation but less effect on root biomass index. As such, seed size 3 reduced fungicide application frequency by 25%. The highest growth vigour, tuber count and yield were observed in seed size 3. Minimal weed species and weeding frequency were observed in plots in which seed size 3 was planted. Additional weeding and fungicide application frequency was required for plots with small size and seed size 1. However, the highest net benefits were observed in seed size 2. Unica had the highest yield as compared to Shangi, K. Mpya and Dutch Robijn.

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Data Availability Data concerning this study can be availed upon request.

Declarations

Competing Interests The authors declare no competing interests.

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