Journal of Agricultural Science; Vol. 12, No. 7; 2020
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Cost Benefit Analyses in Managing Late Blight Through *Trichoderma asperellum* Seed Treatment and Ridomil® Application on Potato

Kilonzi M. Jackson[1], Mafurah J. Joseph[1], Nyongesa M. Wambomba[2] & Ng'ang'a Nancy[2]

[1] Egerton University, Njoro, Kenya

[2] Kenya Agricultural and Livestock Research Organization, Tigoni, Limuru, Kenya

Correspondence: Kilonzi M. Jackson, Egerton University, P.O. Box 536-20115, Njoro, Kenya. E-mail: kilonzijack@gmail.com

Received: October 18, 2019 Accepted: January 10, 2020 Online Published: June 15, 2020

doi:10.5539/jas.v12n7p32 URL: https://doi.org/10.5539/jas.v12n7p32

Abstract

Fungicides overuse in management of late blight has led to increased cost of production and biodiversity issues. To better understand costs and benefits associated with seed treatment to reduce fungicide application, apical cutting and tuber seed crop were pre-treated by either peridermal injection or dipping using *T. asperellum* suspension at 33%, 66% and 100% concentration and then sprayed separately with Ridomil® (Metalaxyl 4% + Mancozeb 64%) at 21, 14 and 7 (Manufacturer's Recommended Regime) days interval. Results showed that apical cuttings had 7.5% higher disease severity and 0.2% lower yield than crop from seed tuber. Untreated and 33% *T. asperellum* were not significant different (p = 0.05) in disease and yield scores. *T. asperellum* concentration at 66% and 100% reduced disease severity by 26% and 27% resulting to 30% and 29% yield increment respectively. Spray interval of 14 days did not differ significantly from 7 day spray interval in terms of disease score and yield but the regime MRR% was double 7 day spray interval. Maximum yield loss was observed in unprotected plots followed by treatments sprayed at 21 days interval. Combination of 66% and 100% *T. asperellum* concentration with 14 days interval resulted to higher yield and marginal rate of return compared to any other combination. Seed dipping was four times profitable than injection. The findings suggest that seed treatment at 66% and 100% *T. asperellum* concentration by dipping in combination with Ridomil® application at 14 days interval significantly reduced late blight epidemics and improved on yield and consequently increased net farm income.

Keywords: seed treatment, apical cuttings, cost and benefit, *Trichoderma asperellum*, Ridomil® (Metalaxyl 4% + Mancozeb 64%)

1. Introduction

Global population is expected to increase up to 9 billion people by 2050 requiring yield increase by up to 100%. The human population increase which is accompanied by decrease in agricultural land as result of land sub divisions and urbanization require sustainable food production practices (Godfray & Charles, 2010). To achieve this goal, development of new and improving existing technologies is essential for more efficient food crop production practices (Foley et al., 2005). Potato is one of the most important vegetable globally in terms of nutrition, socio-economics and creation of employment globally (Wu et al., 2013) and therefore plays a key role in food and nutritional security which is a major concern globally (Devaux & Ortiz, 2014). The tuber crop is grown majorly in highlands where land subdivision is common because of its multiple benefits to smallholder farmers. The crop matures early, yield more per unit area and with more nutritive value than cereal crops (Dersseh et al., 2016). However, potato yield globally is below production potential due to biotic stresses and seed shortage (Guchi, 2015).

Late blight is probably the major yield reducing biotic stress worldwide (Savary et al., 2012) which has tremendous impact on yield and cost of potato production. High rainfall and temperature experienced in potato growing regions that are conducive for *P. infestans* result in short life cycle that cause field defoliation within a week (Rekanović et al., 2011) requiring multiple fungicide application with short interval regime (Majeed et al., 2017). Multiple fungicide application not only raise human and environmental concern but also increase cost of managing the disease than any other input while affecting potato yield globally threatening potato value chain (Sharma & Saikia, 2013). In addition, the pathogen is increasingly becoming resistant to fungicides due to its new aggressiveness nature, high mutation rate and ability to co-evolve with host (Kamoun et al., 2015). Therefore *P. infestans* is a devastating disease that threaten food security (Hu et al., 2012). The annual economic losses attributed to late blight globally is about 170 US billion dollars (Wu et al., 2012) while in Kenya the losses range between 60 to 70% and up to 100% when conducive weather conditions are prolonged (Olanya et al., 2001). The pathogen further cause economic losses by inducing tuber rot that affect a whole lot of in store or after planting that cause early tuber and foliar blight (Kirk et al., 2010). Management of late blight has therefore become a costly necessity in potato producing regions especially during the long rains (Bengtsson et al., 2014).

Formal seed system in Kenya supplies less than 5% of total seed required by farmers per cropping season. The deficit is supplied by informal sector including farm saved seed, buying from their neighbours' and from local market (Gildemacher et al., 2009). Use of farm saved seed as a result of the current recurring shortage of certified seed experienced in Sub Saharan countries accelerate late blight that could result in total crop loss (Muthoni et al., 2017). Croft et al. (2017) reported that higher seed quality results to higher germinability and improved yield. To contribute to improved seed system, modern technology have been developed to produce clean seed including stem and apical cuttings produced through tissue culture techniques (Atkinson & Parker, 2018). However, little is known on cost benefits and performance of apical cuttings in terms of survival rate, yield and late blight susceptibility in field conditions.

Use of disease free seed (Gildemacher et al., 2011), cultural practices including removal of volunteer plants (Gigot et al., 2009), use of biological controls (Syed et al., 2018) and integrated pest management (Xu et al., 2011) offer the most effective and sustainable ways in controlling late blight. Rapid evolution of *P. infestans* which overcome race specific resistance has led to loss of their disease tolerance making use of host resistance alone a non-effective strategy (Forbes, 2012). Fungicides should not be used continuously neither do they represent sustainable practice due to emergence of fungicide insensitive strains (Kamoun et al., 2015). Advocating the use of biocontrol to lower the costs associated in managing this devastating disease while enhancing a more effective and environmental friendly potato production is the most sustainable alternative (Kumar et al., 2014).

Beneficial microorganisms in which genus *Trichoderma* is widely used are increasingly becoming an important component in agricultural ecosystem managing soil borne pathogen (Miles et al., 2012). *Trichoderma* is a fast growing fungi that manage crop diseases by competition, use of cell degrading enzymes and inducing systemic resistance in crops (Janzen, 2011) and stimulate plant immunity as well promote plant growth (Keswani et al., 2014). It is widely studied biocontrol due to its mycoparasitic action against many plant pathogens including *Pythium* species *in vitro* (Hermosa et al., 2011), *Fusarium* species (Abhiram & Masih, 2018), *Rhizoctonia* and *Botrytis* species (Redda et al., 2018). In addition, the biocontrol has been reported to enhance plant growth (Viterbo et al., 2010). Studies have shown that pre-treating seed with a biocontrol reduce seed piece decay and introduction of primary inoculum into field (Wharton et al., 2007; Somani & Arora, 2010). Fatima et al. 2015 found that *Trichoderma harzianum* could reduce growth of *Phytophthora infestans in vitro.* Latent infected tubers affect the number of sprouts as a result of tuber decay or sprout infection affecting yield (Nolte et al., 2003). Seed treatment with biocontrol could reduce sprout infection and late blight epidemics early in the cropping season attributed to latent infection. Powelson et al. (1999) reported that Curzate (cynamoxil 4% and mancozeb 64%) was effective in managing late blight of potato through seed treatment while Wharton et al. (2012) found that *Bacillus subtilis* and *T. harzianum* could reduce late blight epidemics by 54.4% and 86% respectively through seed treatment. Recently, Basahi, (2014) demonstrated that *Pseudomonas* species reduced common scab severity of potato when potato seed is pre-treated before planting. However, there is limited literature on cost benefits accrued to seed treatment with biocontrols to reduce seed infection in combination with fungicide application to protect canopy.

The objectives of the study were therefore to determine the efficacy of *T. asperellum* through seed treatment and foliage protection using fungicide application regime and cost benefit associated with seed treatment in combination with fungicide application. Apical cutting and tuber seed crop and dipping and pericardial injection net benefits were also determined. The results provide imperative information that help in managing late blight effectively with minimal costs as well as improving potato production through this environmental sound technology which is one of the Food Agricultural Organization (FAO) key goal.

2. Methodology

2.1 Study Site

The experiment was conducted during short rains (November to December 2018) and long rains (March to July 2019) at Kenya Agricultural and Livestock Research Organization (KALRO) Tigoni. The station is located at latitude 10°9′22″ south and longitude 36°4′72″ east and receives rainfall of 1800 mm per annum and temperature range from 10 °C to 25 °C. It has an altitude of 2300 m above sea level (Jaetzold et al., 2006).

2.2 Study Materials

Shangi apical cuttings (20 cm in height) and tuber (40-60 g) seed was obtained from KALRO Tigoni. The variety is the most widely grown in Kenya because of its excellent French fries and table consumption. The variety is susceptible to late blight and moderately drought resistant. Ridomil® (Metalaxyl 4% + Mancozeb 64%) belonging to phenylamide group is one of the widely used fungicide to manage late blight in Kenya (Taylor et al., 2013). *Phytophthora infestans* isolation, culturing and bulking was conducted as described by Gregory (1997).

2.3 Production of Apical Cuttings

In vitro plantlets of tissue cultures of *shangi* variety were produced at the plant tissue culture laboratory at KALRO Tigoni. Cultures were maintained on Murashige and Skoog medium (Murashige, 1962) that contained sucrose (3%, w/v) and agar (Technical number 2) in culture bottles. The *in vitro* plantlets were sub cultured at regular interval of 21 days and placed in growth chamber maintained at 18 °C under light intensity 42 mol m^{-2} s^{-1} provided by fluorescent lamps in 18 hours photoperiod regime. To harden off, the *in vitro* plantlets (8-10 cm) were transferred to horticultural germination trays containing peat moss in glass house and covered with polythene paper to enhance uniform humidity. The plantlets were transferred into 300 g cups containing a mixture of sand and coco peat (1:1) after 7 days. Rooted apical cuttings were developed by cutting the apical part (primordial leaf + 2 leaves) of the seedling. Rooting hormone (indole butyric acid) was applied on the stem base and planted *in vitro* tray containing peat moss. This was placed in a grid covered with polythene bag in glasshouse for 10 days. The seedlings were then transferred into the cups described above and placed on the bench in the glasshouse to enhance acclimatization and hardening off for about 3 weeks before field transplanting.

2.4 Seed Treatment

Intact tubers were cleaned with water, rinsed and surface sterilized by dipping in 5% sodium hypochlorite for 15 seconds by dipping. *T. asperellum* at 33% (3.0×10^6 CFU/mL), 66% (7.0×10^6 CFU/mL) and 100% (1×10^7 CFU/mL) concentration the Manufacturer Recommended Rate (MRR) were prepared using pure spore powder obtained from Real IPM, Kenya. *T. asperellum* suspension at rate of 250 g/250 L (MRR) per hectare (100%), 165 g/250 L (66%) and 82.5 g/250 L (33%) was inoculated to tuber seed and apical cuttings by either pericardial injection or dipping separately. The spores were placed on 100 g of sterilized sorghum and allowed to stand for 4 days to initiate sporulation. The inoculated grains were washed with 500 mL of sterilized distilled water and the concentration adjusted to 1×10^7 CFU/mL using hemocytometer for 100% concentration. Mistress 72® at a rate of 2 g L^{-1} (positive control) at MRR suspension was also prepared. Intact tubers were inoculated with 45 µL of the suspension separately by peridermal injection at the apical end about 1 cm away from developing sprout using a 100 µl hypodermic syringe and needle. Witness tubers were inoculated with 45 µl of *P. infestans* suspension (adjusted to 4×10^4 zoospores/ml using hemocytometer) (Chaouch, 2016).

Apical cuttings and intact tubers were cleaned with distilled water and inoculated with the 100% *T. asperellum* concentrations, Mistress 72® (2gL^{-1}) and *P. infestans* described above by dipping for 5 seconds in three litre bucket. Inoculated cuttings were dipped in distilled water ensuring only half of the root length is in water for 24 hours in diffused lit wooden store (18±2 °C) to allow intake of the biocontrol. *P. infestans* was inoculated by dipping the apical cuttings as above and then incubated in the above described store for 24 hours before planting.

2.5 Fungicide Application Regime

Field inoculation with *P. infestans* (1×10^4 zoospores/mL) was done twice using calibrated hand sprayer. Ridomil® application (2.5 g L^{-1}) was initiated on appearance of first late blight symptoms four days after pathogen inoculation which depicts strategy used by the farmers. The fungicide spray regime were; unsprayed (negative control), 21 days interval, 14 days interval and 7 days interval (manufacturer recommended Interval (MRI)). Spray drifts were prevented using a polythene bag of gauge 2.1 placed along the paths while spraying.

2.6 Experimental Layout and Planting

Experimental treatments were laid in randomized complete block design in split split plot arrangement with fungicide application regime, seed type and seed treatment rates been main plot, sub plot and sub sub plot respectively with three replications. Experimental plots measured 3 m x 3 m with 2 m wide path to reduce spray drifts. Four years fallow land was prepared during dry period in both seasons and ridges made two days after onset of rains. Planting was done two days after onset of rains. Each block was separated by a buffer zone of 2 m to prevent fungicide drifts. Di- ammonium phosphate (DAP) was applied at a rate of 450 Kg ha^{-1}. Top dressing with Calcium Ammonium Nitrate (CAN) at a rate of 300 Kg ha^{-1} was done 30 days after emergence during second weeding. All field management practices were uniformly applied to all treatments.

2.7 Disease and Yield Assessment

Late blight severity and incidence assessment was conducted on weekly interval starting 26 days after emergence based on visual disease assessment scale as described by Yao et al. (2016). Disease severity was used to compute Area Under Disease Progress Curve (AUDPC) before converting to Relative Area Under Disease Progress Curve (RAUDPC) (Yuen & Forbes, 2009). At maturity (110 days after emergence) the crop was dehaulmed and each treatment plot harvested separately. The tubers were graded into ware (> 60 g), seed (40-60 g) and chatt (> 40 g) grades as described by KALRO Tigoni grading system which were then counted and weighed using salter scale version 6.2. Plot yield (kg per plot) was converted to tonnes per hectare before cost benefit analysis. Yield was evaluated on marketable tuber grade (> 40 g). Number of tuber infected with blight were also counted and weighed. Tuber infection in each treatment was assessed after harvesting to estimate yield losses and summarized using the below formula:

$$\text{Tuber infected \%} = \frac{\text{Total no. of infected tuber harvested from the plot}}{\text{Total number of harvested tubers}} \times 100 \qquad (1)$$

Percent yield increase over control was assessed using the below formula:

$$\text{Increase in yield \%} = \frac{\text{Yield in treatment} - \text{Yield control}}{\text{Yield in control}} \times 100 \qquad (2)$$

2.8 Data Analyses

Data on time spend on planting per plot (first transformed using $\log_{10}$ transformation) and RAUDPC values were subjected to analysis of variance using Statistical Analysis System (SAS) software version 8.2. Treatments means were separated using Tukey's honest significant difference. Economic analyses were conducted using partial budgeting in Kenyan shillings (KES). Treatment or treatment combination which gave the highest marginal rate of return percentage was classified as the best treatment. The marginal rate of return was calculated using the below formula:

$$\text{MRR \%} = \frac{\text{DNI}}{\text{DIC}} \times 100 \qquad (3)$$

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 DCI is the difference between input cost compared to control [Change in total variable costs (Total variable cost of new technology minus control)].

To compare seed treatment methods and seed type costs and benefits, ratio of net benefits (Gross margin) to total variable costs was calculated using the below formula. Treatment that showed the highest ratio was reported as the best.

$$\text{Cost Benefit ratio} = \frac{\text{Net benefit}}{\text{Total variable costs}} \qquad (4)$$

2.9 Economic Analysis

Partial budgeting was used to determine cost and revenues differences among the treatments (*T. asperellum* seed treatment concentrations and their combinations with fungicide regime, seed type and seed treatment methods). Costs that were applied uniformly to all treatments were not considered (Halloran et al., 2013). Related costs that varied among treatments included planting, seed treatment and fungicide application labour, seed transport, seed, Ridomil®, knapsack hire and *T. asperellum*. Seed and ware grade prices were based on current prices of KALRO Tigoni and Limuru market for seed and ware (farm gate price) for a bag of 50 kg and 100 kg respectively. All costs and revenues were converted to per hectare which was used to calculate marginal rate of return in partial budgeting. Onion nets roll of 600 m/ha was purchased from Limuru agro stockiest. Hypodermal syringes and needles were purchased from local pharmaceutical shop which were sold in packets containing 12 pieces (2 packets/ha).

Planting labour (for tubers and apical cuttings) was determined by allocating workers (3 men and 3 women aged between 30 to 52 years) code A to F to avoid biasness and each planted 5 plots (replications) of 3 m × 3 m. Stop watch was used to record time spend by each worker per plot. Planting of tuber seed was done first followed by apical cutting seed the following day to ensure the worker's energy was about the same level. Planting duration was converted to per hectare before transformation. Labour costs for seed inoculation, planting and spraying were based on Kiambu County labour wages scheme. Costs associated with Ridomil® and application labour was based on the application frequency.

3. Results

3.1 Effects on Late Blight Management

3.1.1 Effects of Seed Treatment Rate and Fungicide Application Regime on Late Blight Severity

The long rain season had an average lower temperatures (17-20 ºC) and higher Relative Humidity (RH) (86%) than short rain season (19-24.5 ºC and 65% RH) which provided conducive conditions for *P. infestans* epidemics. Weather variation resulted in higher disease severity during the long rain season of up to 100% compared to the short rains (54%) in the negative control. In the first three weeks after emergence, disease severity was uniform on the crop but differed among the spray regime associated treatments from the fourth week. The rate of disease increase was higher by 54% in unsprayed associated treatments than fungicide protected treatments. Apical cuttings and tuber seed were not significant different ($p = 0.05$) in terms of disease response and yield during short rains unlike during long rains where apical cuttings had 7.4% higher disease score and tuber infection than tuber seed crop.

Table 1 shows unsprayed had the highest disease score values followed by 21 days interval Ridomil® application. Highest disease reduction and improved yield over control was observed in 14 days and 7 days interval. 21 days interval disease and yield score was intermediate between unsprayed and 14 days interval while 14 and 7 (MRR) days interval did not differ significantly. Both seed treatment and fungicide application contributed to additional yield but higher additional yield was observed in fungicide application than seed treatment (Table 2). Yield and disease severity score observed in 33% *T. asperellum* concentration and the negative control were not significantly different ($p = 0.05$). *T. asperellum* at concentration of 66%, 100% and Mistress 72® had the lowest late blight severity and highest yield. On average seed treatment with Mistress 72® and *T. asperellum* at 100%, 66% and 33% concentration contributed to 21%, 21%, 19% and 5% yield increase respectively. There was a strong negative correlation ($r = 0.93$) between *T. asperellum* concentration and RAUDPC (Figure 1). Combination of 7 and 14 days interval with seed treatment at 66% and 100% *T. asperellum* concentration and Mistress 72® had the highest disease reduction (Table 1) and improved yield (Table 7).

Seed, ware and chart grades differed significantly among the treatments. Unsprayed had the highest chart grade proportion relative to seed and ware grade compared to the 21, 14 and 7 days interval. Compared to untreated control, *T. asperellum* at 100% and 66% concentration also contributed to increased marketable tuber size. Tuber infection was only reported in unsprayed treatments.

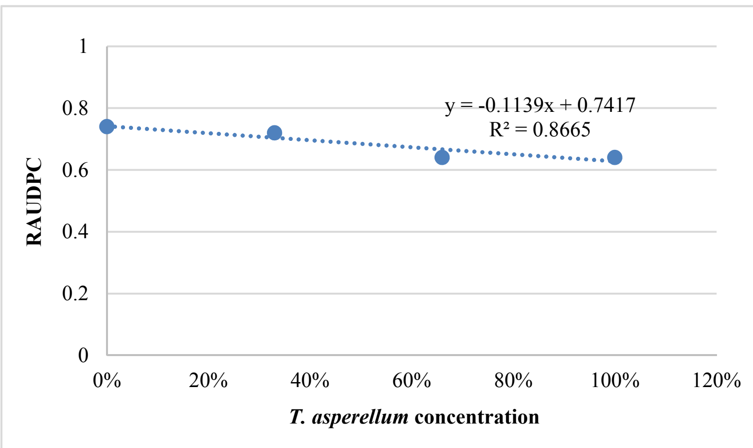

Figure 1. Correlation between *T. asperellum* concentration and Relative Area Under Disease Progress Curve (RAUDPC)

Table 1. Effects of *T. asperellum* seed treatment on late blight severity (RAUDPC) and marketable yield (t ha^{-1}) in apical cutting and tuber seed

Seed	Treatment rate	(RAUDPC Means±Standard Error)							
		Short rains season				Long rains season			
		Unsprayed	7 days	14 days	21 days	Unsprayed	7 days	14 days	21 days
Tuber	Untreated	0.38±0.009 a	0.25±0.012a	0.28±0.009a	0.30±0.019a	0.72±0.012a	0.46±0.019a	0.49±0.022a	0.58±0.017a
	33%	0.36±0.012b	0.23±0.013a	0.26±0.003a	0.28±0.012a	0.71±0.015a	0.46±0.024a	0.47±0.023a	0.56±0.029a
	66%	0.26±0.017c	0.12±0.007b	0.15±0.007b	0.16±0.009b	0.60±0.003b	0.38±0.028b	0.38±0..007b	0.50±.0.019
	100%	0.23±0.007c	0.11±0.003b	0.14±0.009b	0.15±0.006b	0.61±0.003b	0.38±0.027b	0.38±0.003b	0.50±0.019b
	Mistress 72	0.23±0.009c	0.11±0.009b	0.14±0.001b	0.16±0.012b	0.60±0.006b	0.54±0.027b	0.37±0.003b	0.50±0.019b
Apical cuttings	Untreated	0.38±0.007a	0.25±0.009a	0.30±0.018a	0.33±0.006a	0.74±0.013a	0.51±0.026a	0.54±0.018a	0.61±0.006a
	33%	0.35±0.012b	0.24±0.009b	0.28±0.012a	0.31±0.009b	0.72±0.010a	0.45±0.020a	0.52±0.023a	0.60±0.007a
	66%	0.26±0.007c	0.10±0.006c	0.14±0.007b	0.16±0.003c	0.64±0.006b	0.44±0.027b	0.45±0.038b	0.54±0.003b
	100%	0.23±0.012cd	0.10±0.007c	0.13±0.007b	0.16±0.006c	0.64±0.009b	0.45±0.024b	0.44±0.047b	0.53±0.012b
	Mistress 72	0.23±0.007d	0.10±0.007c	0.14±0.009b	0.16±0.006c	0.63±0.009b	0.49±0.021b	0.45±0.040b	0.54±0.009b
CV%		4.09				11.85			

Note. Letters followed by same letter within the same column indicate treatments are not significantly different.

Table 2. Effect of spraying regime and seed treatment on yield (t ha^{-1})

Regime, Treatment/Season	Unsprayed	21 days interval	14 days interval	7 days interval	HSD	Untreated	33%	66%	100% *T. asperellum*	Mistress 72®	HSD	CV%
Short rain	1.1a	14.2b	24.0c	24.0c	1.067	13.4a	13.5a	17.2b	17.5b	17.5b	1.269	9.9
Long rain	0.73a	8.8b	20.1c	20.5c	0.529	11.7a	12.0a	12.9b	13.0b	13.0b	0.630	6.2
Additional yield	Short rain	11.91	20.82	20.82			0.07	0.28	0.31	0.31		
	Long rain	11.05	26.53	26.53			0.03	0.10	0.11	0.11		

Note. Letters followed by same letter within same row indicate treatments are not significantly different.

3.1.2 Effect of Seed Treatment Method on Late Blight Disease and Yield

Higher disease severity was recorded in peridermal injection seed treatment than dipping but peridermal injection had the highest yield (Table 3). Untreated had the highest disease score and lowest yield compared to Mistress 72® and *T. asperellum* at 100% concentration. There was no significant different ($p = 0.05$) in disease response between Mistress 72® and 100% *T. asperellum* seed treated crop. The lowest disease score and highest yield was observed in 14 and 7 days interval when combined with Mistress 72® and 100% *T. asperellum* concentration (Figure 2).

Table 3. Significant difference in disease severity and yield between perdermal injection and dipping during short and long rain season

Seed treatment method	**Means**			
	Short rain season		**Long rain season**	
	RAUDPC	**YIELD (t ha^{-1})**	**RAUDPC**	**YIELD (t ha^{-1})**
Peridermal injection	0.191a	18.41a	0.500a	15.28a
Dipping	0.172b	14.67b	0.466b	14.01b
HSD (p=0.05)	0.005	0.556	0.019	0.406
CV%	6.01	7.06	8.23	5.82

Note. Letters followed by same letter within the same column indicate the treatments do not differ significantly.

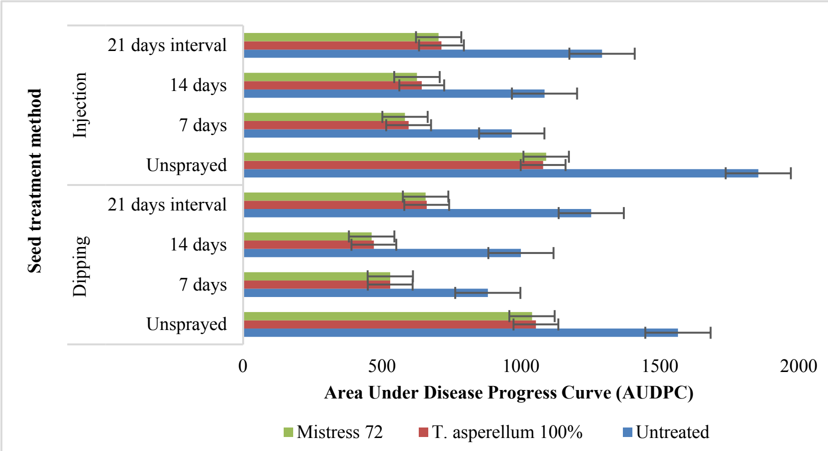

Figure 2. Effect of seed treatment method on late blight severity (AUDPC)

3.2 Costs and Revenues

The cost of apical cutting (44,440 plants ha^{-1}) and tuber seed (45 bags ha^{-1}) was Kes 10 per seedling and Kes 3,000 per bag respectively. There was no significant different ($p = 0.05$) in time spend on planting among the workers both in apical cuttings and tuber seed despite their age differences. Average planting time spent on apical cutting and tuber seed per hectare differed significantly ($p = 0.05$). On average, 6 and 14 man days working 8 hours per day were taken planting tuber seed and apical cuttings per hectare respectively (Table 4). Figure 3 shows more time was taken in planting apical cuttings than tuber seed by each worker. Inoculation by dipping took half man days for 2 bags (11¼ man days ha^{-1}), while pericardial injection took one man day per 500 tubers (½ bag) translating to 90 man days ha^{-1}. 1,680 apical cuttings inoculation took half man day translating to 13 man days per hectare. A rate of Kes 300 per man day was adopted in planting, seed treatment and other field management practices except fungicide application. The biocontrol is packaged into 200 g (Kes 1,160), 100 g (Kes 600) and 50 g (Kes 350). 16 g ha^{-1} pure spores of *T. asperellum* was used for peridermal inoculation. Ridomil® was purchased at Kes 3000 per kilogram and applied at a rate of 2.5 kg ha^{-1}. 7, 14 and 21 days interval resulted in 8 (20 kg ha^{-1}), 4 (10 kg ha^{-1}) and 3 (7.5 kg ha^{-1} of Ridomil®) applications respectively. A packet of syringe and a roll of onion netted bag was purchased at Kes 320 per packet and Kes 2000 per roll respectively at Limuru local agrostockist.

Labour for fungicide application was Kes 400 per man day (4 man days/ha) while knapsack hire according to report from Ministry of Agriculture Limuru, Kiambu data was Kes 50 per hectare per day. According to transport costs data collected from Ministry of Agriculture Limuru, Kiambu and private transporters on transport costs, it costs on average Kes 15 per tonne per kilometre for tuber seed transport while apical cuttings box containing 1200 cuttings from stockman rozen transported by G4S courier costs Kes 12 per box per kilometre. Farm gate prices for seed and ware potato was Kes 2,000 for 100 kg bag (Data from Ministry of agriculture Limuru). Average yield (t ha^{-1}) was adjusted by 10% before cost benefit analysis to approximately match field yield obtained by farmers (Muchiri et al., 2017).

Unsprayed associated treatments yield was lower than the farmers' average yield (8 t ha^{-1}) (Gildemacher et al., 2011) as shown in Figure 4 and therefore was not considered in the economic analysis (Namanda et al., 2004). Potato prices for both ware and seed remained constant in both seasons.

Table 4. Time (hours) spend in planting tuber and apical cuttings per hectare

Worker	Transformed data		Untransformed data	
	Tuber	Apical cutting	Tuber	Apical cutting
A	1.70a	2.12 a	55.60 a	134.64 a
F	1.68 a	2.00 a	49.72 a	100.54 a
E	1.67 a	1.98 a	49.28 a	95.70 a
D	1.65 a	2.06 a	45.98 a	121.00 a
C	1.56 a	2.04 a	36.30 a	108.68 a
B	1.55 a	2.06 a	35.86 a	124.96
Mean			45.47	114.25
HSD (p = 0.05)	0.18	0.21	22.57	71.25
CV%	5.66	5.11	22.75	31.37

Note. Letters followed by same letter within same column indicate the treatments do not differ significantly

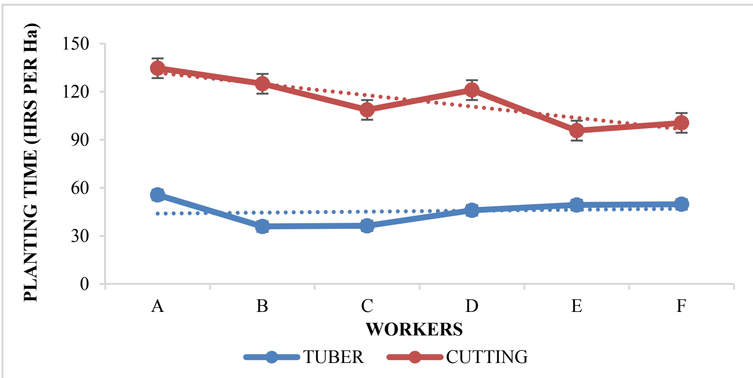

Figure 3. Time spend by each worker in planting tubers and apical cuttings seed. Letters A to F represents workers codes

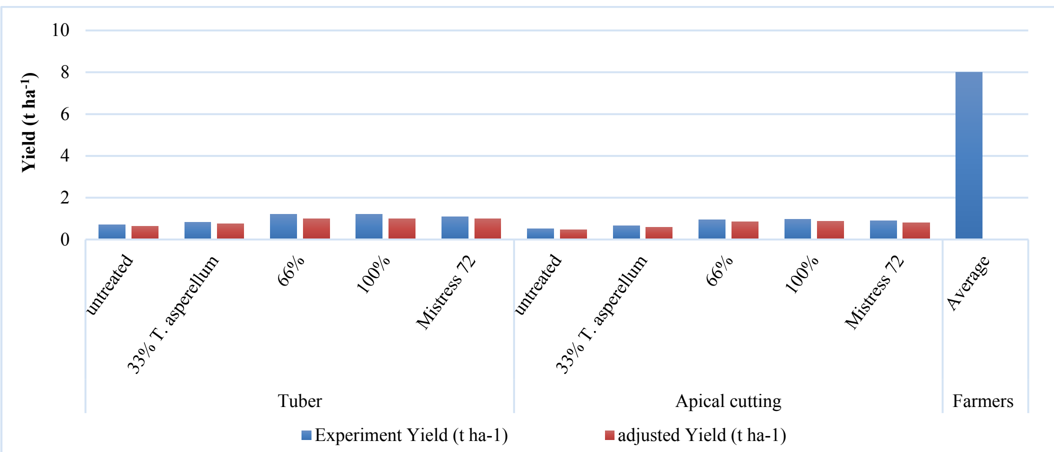

Figure 4. Yield response from unsprayed tuber and apical cutting seed crop compared with farmers average yield

3.3 Cost Benefit

3.3.1 Spray Regime and Seed Treatment Concentration

There was an increase in tuber size associated with disease control compared to unprotected plots. Harvest from the unsprayed plots consisted of 78% chatt size grade while fungicide application at 21, 14 and 7 days interval comprised chatt grade proportion of 2.43%, 2.04% and 0.91% the total yield respectively. The standard program was not significantly different in terms of yield from 14 day spray interval (Figure 5). Untreated and 33% *T. asperellum* yield composed of a large proportion of chatt size compared to *T. asperellum* at 66% and 100%

concentration (Figure 6). Partial budget indicated that 7, 14 and 21 day spraying interval regime had positive marginal rate of return and short rain season had a higher marginal rate of return than long rain season. The highest marginal rate of return percent (MRR%) was obtained from 14 days that had 815% and 753% during short and long rain season. Seasonal variations resulted in marginal rate of return percent differences between 21 and 7 day spraying interval. Spraying interval of 21 days interval had higher MRR% of 520% during short rain season than 7 day interval that had 406% but during long rain season, 7 day interval had MRR% of 360% while 21 days interval had 317%. *Trichoderma asperellum* at 66% concentrations had a higher MRR% in all spray fungicides regimes than *T. asperellum* at 100% concentration during short rain season but during long rain season it was vice versa (Table 10). Therefore, the highest returns were obtained from *T. asperellum* at 66% and 100% concentration when combined with 14 days interval.

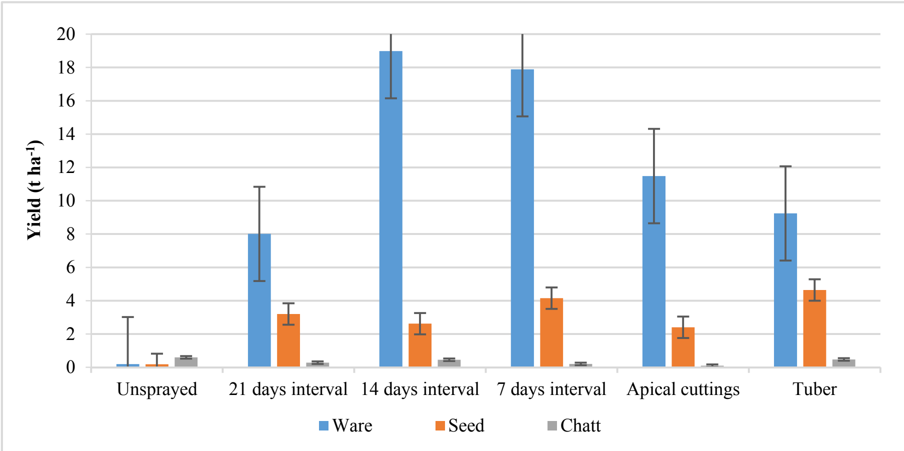

Figure 5. Effect of spray regime on potato grades

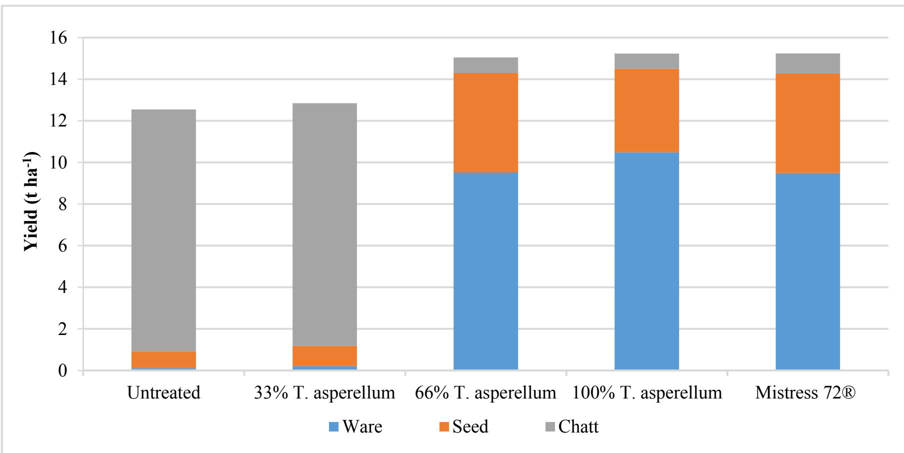

Figure 6. Effect of *T. asperellum* concentrations on potato tuber grade

Table 5. Cost benefit analysis (Kes ha^{-1}) on tuber seed treatment with *Trichoderma asperellum* by dipping in combination with Ridomil® application

Variable	Unsprayed	7 days interval			14 days interval			21 days interval		
	0%	0%	66%	100%	0%	66%	100%	0%	66%	100%
Sales										
SR yield (t ha^{-1})	0.83	21.77	24.97	25.14	19.74	24.85	25.06	10.45	16.79	16.88
SR Adjusted yield (t ha^{-1})	0.75	19.59	22.47	22.63	17.77	22.37	22.55	9.40	15.11	15.19
LR Yield (t ha^{-1})	0.60	19.63	21.43	21.69	18.24	21.43	21.83	7.07	9.52	9.92
LR adjusted Yield (t ha^{-1})	0.54	17.67	19.29	19.52	16.41	19.29	19.65	6.36	8.57	8.93
Gross field benefits SR(Kes)	15 000	391 800	449 400	452 600	355 400	447 400	451 000	188,000	302,200	303,840
Gross field benefit LR (Kes)	10 800	353 400	385 800	390 400	328 200	385 800	393 000	127,200	171,400	178,600
Costs (Kes)										
Trichoderma	0	0	1 160	1 510	0	1 160	1 510	0	1,160	1,510
4 Knapsacks hire	0	1 600	1 600	1 600	800	800	800	600	600	600
Ridomil®	0	60 000	60 000	60 000	30 000	30 000	30 000	22,500	22,500	22,500
Labour(Kes)										
Seed treatment	0	0	3 300	3 300	0	3 300	3 300	0	3,300	3,300
Spraying	0	12,800	12 800	12 800	6 400	6 400	6 400	4,800	4,800	4,800
Total costs (Kes)	0	74 400	78 860	79 210	37 200	41 660	42 010	27,900	32,360	32,710
Net benefits for SR (Kes)	15 000	317 400	370 540	373 390	318 200	405 740	408 990	160,100	269,840	271,130
DNI SR (Kes)		302 400	53 140	55 990	303 200	87 540	90 790	145,100	109,740	111,030
DCI (Kes)		74 400	4 460	4 810	37 200	4 460	4 810	27,900	4,460	4,810
SR MRR%		406	1 191	1 164	815	1 963	1 888	520	2461	2308
Net benefits LR (Kes)	10 800	279 000	306 940	311 190	291 000	344 140	350 990	99,300	139,040	145,890
DNI LR(Kes)		268 200	27 540	32 190	280 200	53 140	59 990	88,500	39,740	46,590
DCI (Kes)		74 400	4 460	4 810	37 200	4 460	4 810	27,900	32,360	32,710
LR MRR%		360	626	669	753	1191	1247	317	123	142

Note. DNI, DCI and MRR% represent difference in net income, difference in input cost and marginal rate of return percentage respectively while SR and LR represent short rain and long rain respectively. 0%, 66% and 100% are *T. asperellum* concentrations. Unsprayed, 7, 14 and 21 represent fungicide spray interval.

3.3.2 Comparison Between Apical Cutting and Tuber Seed Crop

Apical cutting had a higher yield both in ware (12.43 t ha^{-1}) and seed (10 t ha^{-1}) grades than tuber seed that recorded yield of 9.43 t ha^{-1} and 11.14 t ha^{-1} for ware and seed respectively during the short rain season (Figure 5). Tuber seed had a net benefit ratio of 1.06 and 0.72 during short and long rain season respectively while with apical cuttings net loss was observed. Apical cuttings (superior in health status to seed tuber) had higher proportion of ware sized yield than seed grade than what was observed in tuber seed crop (Table 6). Therefore if the seed grade was sold at prevailing seed price it would not be profitable. The cost apical cutting seed, transport and planting labour was about 80%, 70% and 72% higher than similar costs associated with tuber seed crop (Figure 7).

Table 6. Cost benefit analysis on apical cuttings and tuber seed crop marketable grade size

Variable	Short rain season		Long rain season	
	Tuber	Apical cuttings	Tuber	Apical cuttings
Yield (t ha^{-1})	15.62	15.99	13.09	11.98
Adjusted yield (t ha^{-1})	14.06	14.39	11.78	10.78
Gross field benefit(Kes)	281 200	287 800	235 600	215 000
Costs				
Seed (Kes ha^{-1})	135 000	444 440	135 000	444 440
Transport (Kes/hectare volume/Km)	68	444	68	444
Labour (Kes ha^{-1})				
Planting	1 800	4 200	1 800	4 200
Total variable costs (TVC)	136 868	449 084	136 868	449 084
Net benefits (NB)	145 000	-161 284	98 732	-234 084
(NB/TVC)	1.06	Loss	0.72	Loss

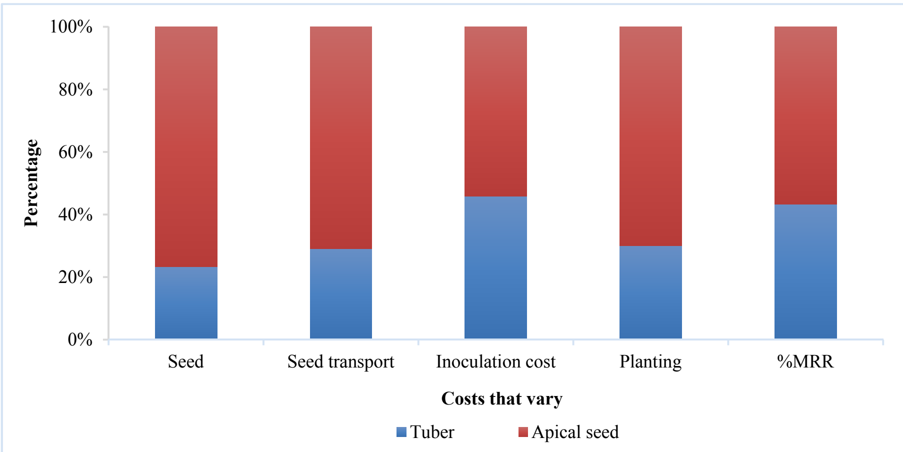

Figure 7. Costs that vary and percentage marginal rate of return between tuber and apical cutting in seed production

3.3.3 Comparison Between Pericardial Injection and Dipping Tuber Seed Treatment

Seed dipping had 408% higher cost benefit ratio than peridermal injection despite higher yield in peridermal injection. Seed treatment labour contributed to 98% of the total variable cost in peridermal as opposed to soaking (63%) (Table 7).

3.4 Estimation of Yield Increase

Higher additional yield increase was observed in tuber seed crop compared to apical cuttings. 7 and 14 days followed by 21 days interval associated treatments had the highest yield. 7 days interval in combination with 66% and 100% *T. asperellum* concentration had the highest additional yield followed by 14 days interval in relation to unsprayed untreated treatment in both apical cuttings and tuber seed crop (Table 8).

Table 7. Percent additional yields associated with fungicide regime, seed type and seed treatment on apical cuttings and tuber seed crop

Regime (days interval)	Seed treatment	Tuber seed crop				Apical cuttings seed crop			
		Short rain season		Long rain season		Short rain season		Long rain season	
		Yield (t ha^{-1})	Yield increase (%)	Yield (t ha^{-1})	Yield increase (%)	Yield (t ha^{-1})	Yield increase (%)	Yield (t ha^{-1})	Yield increase (%)
7	Mistress	25.30±0.26a	2 948	21.56±1.03a	3 493	27.24±0.25a	4 229	20.37±0.48a	4 637
	100%	25.14±0.30a	2 929	21.69±0.70a	3 515	27.22±0.31a	4 221	20.10±035ab	4 574
	66%	24.97±0.30a	2 908	21.43±0.83a	3 472	26.78±0.30a	4 151	19.71±0.35ab	4 484
	33%	21.09±1.14b	2 441	20.63±0.83a	3 338	20.87±1.57b	3 213	19.04±0.40bc	4 328
	untreated	20.77±1.04b	2 402	20.63±0.74a	3 338	20.70±1.46b	3 186	18.65±0.40c	4 237
14	Mistress	24.91±0.31a	2 901	21.83±1.05a	3 538	27.30±0.18a	4 233	19.84±1.05a	4 514
	100%	25.06±0.30a	2 913	21.83±1.21a	3 538	27.08±0.17ab	4 198	19.71±0.26a	4 483
	66%	24.85±0.42a	2 894	21.69±1.15a	3 515	26.89±0.31b	4 168	19.71±0.27a	4 483
	33%	20.81±1.02b	2 407	20.50±1.26a	3 317	21.10±1.14c	3 249	19.71±0.48a	4 483
	untreated	20.74±1.03b	2 399	20.24±1.00a	3 273	21.16±1.58c	3 259	18.91±0.48a	4 298
21	Mistress	16.79±0.94a	1 923	10.05±0.13a	1 575	15.58±0.59a	2 373	9.13±0.40a	2 023
	100%	16.88±0.99a	1 934	9.92±0.23ab	1 553	15.89±0.58a	2 422	8.99±0.35a	1 991
	66%	16.35±0.87a	1 870	9.52±0.01b	1 487	15.62±0.58a	2 379	8.99±0.26a	1 991
	33%	11.60±2.82b	1 298	8.33±0.01c	1 288	10.96±2.54b	1 640	7.67±0.53b	1 684
	untreated	11.45±2.79b	1 280	8.07±0.50c	1 245	10.58±2.71b	1 579	7.41±0.48b	1 623
Unsprayed	Mistress	1.37±0.19a	65	0.90±0.07a	50	1.13±0.16a	79	0.67±0.06a	56
	100%	1.39±0.34a	67	0.93±0.06a	55	1.17±0.17a	86	0.76±0.06a	77
	66%	1.36±0.16a	64	0.99±0.01a	65	1.08±0.09a	71	0.79±0.04a	84
	33%	0.93±0.06b	12	0.74±0.15b	23	0.79±0.10b	25	0.52±0.10b	21
Control	untreated	0.83±0.04b		0.60±0.21b		0.63±0.08b		0.43±0.11b	
CV%		6.72		11.85		6.72		11.85	

Table 8. Cost benefit analysis (Kes ha^{-1}) on pericardial and dipping seed treatment methods

Variable	Short rain season		Long rain season	
	Injection	Dipping	Injection	Dipping
Yield (t ha^{-1})	15.47	12.13	14.48	13.09
Adjusted yield (t ha^{-1})	13.92	10.92	13.03	11.78
Gross field benefits (Kes)	278 400	218 400	260 600	235 620
Costs (Kes)				
Hypodermal syringe	640	0	640	0
Onion bag	0	2 000	0	2 000
Labour				
Seed treatment	27 000	3 375	27 000	3 375
Total variable cost	27 640	5 375	27 640	5 375
Net Benefit	250 760	213 035	232 960	230 245
(NB/TVC)	9.07	39.63	8.43	42.84

4. Discusion

4.1 Late Blight Management

4.1.1 Effects of Seed Treatment Rate and Fungicide Application Regime on Late Blight Severity

Late blight has been the most devastating disease of potato for the last decades with a potential of causing 100% yield loss affecting both seed and ware potato industry. Efforts in developing integrated disease management has been directed in minimizing excessive fungicides usage. Numerous strategies have been studied including combination of nutrition with fungicides (Mosota et al., 2017), use of biological controls (Kohl et al., 2019; Akhtar & Siddiqui, 2008) and use of disease free seed materials (Wang et al., 2017) globally for production seed and ware potato to reduce *P. infestans* inoculum in potato field while minimizing use of pesticides. However, none of the scientists have established the profitability of the new practice or combination of the strategies. The additional practices result in additional costs whose ultimate benefits need to be studied. Avoiding yield losses caused by biotic and abiotic stresses is the major strategy in promoting food security with available resources (Lobell et al., 2009). The present study attempts to determine efficacy as well as cost effectiveness in combining seed pre-treatment seed with fungicide application regime in effort to reduce the number of fungicide application.

Late blight symptoms were observed from establishment to tuber bulking phase suggesting that the disease infect potatoes at any stage of the crop which was in agreement with Tadesse (2018) results. Higher disease score was reported during long rain season that significantly reduced apical cutting yield more than tuber seed. Apical cuttings during long rains were infected by late blight first because were already in vegetative phase at planting resulting to higher disease increase rate. This shows apical cuttings could be vulnerable to late blight than crops from seed tuber. The study did not explore the cause of vulnerability but speculates that crop from seed tuber have food reserve to support higher crop vigour and established rooting systems which draw nutrients offering inherent capacity to tolerate late blight to a certain degree. Previous study reported that appearance of late blight symptoms in the first 10-12 days after emergence lead to severe epidemics resulting in 80-100% foliage damage (Norkotah, 2002). Norkotah (2002) further observed that late or mid infections result in less severe epidemics and less yield loss as it was observed during short rain season. *T. asperellum* at 66% and 100% concentration was able to delay late blight infection while reducing the number fungicide applications by increasing the spray interval by 7 days.

Seed treatment not only reduced seed decay but also protected sprouts from late blight infection early in the cropping season. *T. asperellum* could have acted against *P. infestans* through competition, antibiosis and enzymatic activities as reported by Itachi et al. (2007) who found that *T. asperellum* induced mycoparasitism and competition against bakanae disease (*Giberrella fujikuroi*) in rice. For successful pathogen suppression, the biocontrol should be at optimum concentration to secrete sufficient defence and antifungal metabolites (López-Bucio et al., 2015). *T. asperellum* at 66% and 100% concentration was able to provide sufficient metabolites adequate for antifungal activities against *P. infestans.* Latent infection cause sprout and foliage infection resulting to early late blight epidemics (Gigot et al., 2009). Therefore delaying late blight infection early in the season through seed treatment could reduce the number of fungicide applications per cropping season. Unsprayed pre-treated crop had the lowest yield as a result of higher disease severity compared to 7, 14 and 21 days interval. This suggests that seed treatment alone was not effective in managing late blight. The highest disease severity reduction was observed on 7 days interval spray followed by 14 days interval. 21 days interval had an intermediate disease and yield score. This could be attributed to the extended fungicide application to the late phase of plant growth just before senescence (Namanda et al., 2004). The findings are in agreement with Siddique et al. (2016) who reported that 7 days interval was sufficient for late blight management. The spray regime confirms importance of fungicide for the control of late blight which corresponded to Kirk et al. (2001) findings. It was observed that untreated treatment sprayed at 7, 14 and 21 days interval had the highest disease score and lowest yield indicating contribution of seed treatment to yield formation. This suggests that seed treatment alone nor fungicide alone could manage late blight effectively. Combination of *T. asperellum* at either 66% or 100% concentrations with 7 and 14 days interval fungicide application interval could offer better management strategy.

Seed treatment therefore increased fungicide application interval from the recommended interval (7 days) to 14 and partially 21 days interval. The results are in agreement with Kirk et al. (2001), Nærstad et al. (2007) and Forbes (2013) who evaluated effect of host resistance on reduced fungicide rates and frequencies application to manage late blight on potato. Liljeroth et al. (2016) reported potassium and phosphite salts increased fungicide application interval by double. Results from the current study indicate that prior seed treatment improves the yield of potato through the management of late blight. Similar results were reported by Wharton et al. 2012 on *Bacillus substilis* and *T. harzianum* in managing late blight through seed treatment by slice piece. Recently Carrero-carr et al. (2016) and Redda et al. (2018) found that *T. asperellum* could suppress Verticillium wilt and fusarium wilt, botrytis and Rhizoctonia respectively. Moreover Viterbo et al. (2010) reported that *T. asperellum* promoted plant growth when inoculated on the seed. Therefore this study suggests that exploring efficacy of *T. asperellum* could widen its spectrum against many pathogens that could be commercially prepared for disease and crop yield improvement.

Trichoderma species have beneficial effects in growth promotion, delayed senescence and increased chlorophyll content (Laila et al., 2014). This was demonstrated in untreated plots which had rapid infection and defoliation of the canopy during long rains. Increased *P. infestans* on canopy as crop matures could be attributed to drain of sugars foliage to tubers during tuber bulking hence affecting the plants immunity (Gao & Bradeen, 2016). Jiang et al. (2017) in their studies found that seed treatment with Revus (*Bacillus Subtilis*) was able to manage late blight and pink rot while Andreu and Caldiz (2006) and Caldiz et al. (2007) found that seed treatment with fungicide was effective on tuber latent infection prior to planting. However with the emergence of fungicide resistant strains and biodiversity concerns could exacerbate the control strategy. Therefore use of biocontrol in seed treatment could be essential in managing late blight epidemics.

4.1.2 Effect of Seed Treatment Method on Late Blight Disease and Yield

Peridermal injection disease severity was 7.3% higher than soaking but 9.1% higher yield was obtained from peridermal injection. The additional disease inoculum observed in peridermal injected treatments did not influence yield formation. The results are in tandem with (Wu et al., 2013) report that showed that biocontrols could improve on yield when used in disease management. *Trichoderma* species mycoparasitic activity depends on secretion of complex metabolites that degrade host cells and exerts competition against phytopathogens (Space and nutrients), promote plant growth and induce plant defensive mechanism (Qiu et al., 2017). *T. asperellum* was not only able to penetrate through the skin and induce disease resistance, promote growth and protect the sprouts but also prevented *P. infestans* attachment on the potato tissues. Seed inoculation by peridermal injection uniformly introduced the biocontrol within tuber tissues that allowed fast action without spending energy penetrating the hard skin. *T. asperellum* was uniformly translocated and in sufficient amounts unlike dipping where there is reduced period of interaction between internal tuber tissues protecting sprouts. Various scientists have explored seed treatment to manage crop diseases. Andreu and Caldiz (2006) reported control of *P. infestans* with fungicide through seed treatment and foliage protection. Basahi (2014) showed that common scab severity was reduced by *Pseudomonas* species through seed piece treatment. Wharton et al. (2012) reported successes in managing late blight through seed piece treatment by dipping using a combination of biocontrols while Hollywood, 2014 reported dipping and peridermal injection were not significantly different in terms of yield. However, the scientists were not able suggest cost effective seed treatment method and therefore this fills such study gap.

4.2 Cost Benefit Analysis

The present study determined the cost benefit accrued to the *T. asperellum* seed treatment at 66% and 100% concentration, combination of *T. asperellum* with fungicide and Ridomil® application regimes. The study further explores on the benefits associated with the use of superior seed material in terms of health status (rooted apical cuttings) and seed treatment methods (dipping or pericardial injection) to enhance improved net farm income. Partial budgeting using marginal rate of return is simple to determine profitability of new technology or combination of practices using additional costs and returns which could be easily understood by farmers (CIMMYT, 1998). The method has been used by several scientists including Kassa and Bayene (2001), Carroll et al. (2009), and Kumar et al. (2015).

4.2.1 Spray Regime and Seed Treatment Concentration

Severe epidemics as a result of prolonged conducive conditions (Whisson et al., 2016) resulted in small tuber size grade affecting marketable grade due to complete defoliation which ultimately affected farm returns (Bussan et al., 2007) as observed in unsprayed treatments. Yesuf and Desta (2015) reported that defoliation by late blight led to 52.94% yield decline in unsprayed. Deahl and Inglis (1993) findings who reported reduction in yield as a result of leaves loss due to defoliation. Fungicide application at 14 and 7 days effectively suppressed *P. infestans* while seed treatment with *T. asperellum* offered prior protection which was also reported by Komy et al. (2015) resulting in higher additional yields than unprotected plots. Pre-treatment contributed to maximum tuberization and enlargement resulting in more marketable tubers. The observation was also in agreement with the results obtained by Hijri (2016) who found that seed inoculation with arbuscular mycorrhiza resulted in 10% yield increment.

The highest MRR% was observed in treatments sprayed at 14 days interval in both seasons despite yield been not significantly different from 7 day spray interval. Fungicide application at 21 and 7 day spray interval was affected by seasonality which also differed in late blight management and yield gained. Higher MRR% was attributed to the additional yield obtained from the treatments. Late blight management using fungicide application at 21 day spray interval during short rain season resulted in additional yield higher than during long rain season which was able to pay the additional costs than what 7 day spray interval managed to recompense resulting in higher marginal rate of return. Ridomil® application at 14 day spray interval reduced costs of purchasing Ridomil® and application labour by half relative to 7 day spray interval regime which leading to higher returns. Namanda et al. (2004) reported increase in yield as a result of fungicide application on weekly interval but observed higher total variable costs associated with the weekly spray interval compared to biweekly spray interval which resulted in saved costs of Ridomil® (KES 3000) and fungicide application associated costs (KES 2,600). This increased net benefits accrued to 14 days interval but dependent greatly on weather conditions. Flannery et al. (2004) also reported cost saving of KES 34,200 per hectare from fungicide application reduction using genetic modified potato.

The results of the present study suggest that seed pre-treatment contributed to improved returns. Seed treatment with *T. asperellum* at 66% and 100% concentration both had a positive MRR% higher than 100% as well higher net benefits than the untreated crops. The findings are in contrast with Hijri (2016) findings who reported seed treatment did not improve on net income. Seed treatment with *T. asperellum* at 100% and 66% concentration had a variable MRR% between long and short rain season spray regime. This could be attributed to higher efficiency in late blight management in crops treated with *T. asperellum* at 100% than *T. asperellum* at 66% during long rains when the conducive conditions for *P. infestans* were prolonged increasing disease severity than during short rains. Improved disease control with *T. asperellum* at 100% concentration resulted in increased yield though not significantly different from *T. asperellum* at 66% concentration, the additional yield was able to pay for the additional costs associated with the treatment thereby giving a higher marginal rate of return. During short rain season, additional yield observed in *T. asperellum* at 66% concentration treatment gave higher marginal rate of return than *T. asperellum* at 100% concentration. This indicates that, even though the two treatment yield was not significantly different, using *T. asperellum* at 100% concentration could be more beneficial and advantageous where conditions conducive for late blight are prolonged. On the other hand, Fungicide application in combination with seed treatment had a higher marginal rate of return compared to crops from untreated seed sprayed with Ridomil® and unsprayed crops. Seed treatment and fungicide application contributed to additional yield which resulted in improved returns consequencely reducing the number of fungicide application in the cropping season. Similar results were observed by Carroll et al. (2009) who found that border treatment resulted in reduced insecticide application on aphids (*Myzus* species).

4.2.2 Comparison Between Apical Cutting and Tuber Seed Crop

The formal seed sector in Kenya provides less than 5% of certified seed (Gildemacher et al., 2009) leaving the informal sector to meet the deficit by farm saving and buying from local market that are mostly latently infected by diseases including late blight (Gildemacher et al., 2011). Tissue culture has a potential of reducing the seed supply gap through rapid multiplication (El-Helaly, 2012). However, little has been documented on their cost benefit over conventional (tuber) propagation methods. Rooted apical cuttings produced through tissue culture has been proposed to have a potential of reducing the seed supply gap using rapid multiplication technology while managing disease incidences (El-Helaly, 2012). However, little has been documented on their cost benefit over conventional propagation method that involves use of seed tuber. In the present study, results suggest that apical cuttings had higher yield during short rain season than tuber seed crop. This is against Benz (1995) findings who reported higher yield in tuber seed crop than apical cuttings. However, the greatest proportion of the costs was attributed to purchase of the seedlings and planting labour resulting in net loss. The study concludes that, the use of rooted apical cuttings either for seed or ware production without recycling the seed would result to net loss. Higher gross profit in the crops from seed tuber was attributed to higher yield against lower cost of seed and planting labour compared to rooted apical cuttings. During long rain season, survival rate of rooted apical cuttings also contributed to lower yield as affecting plant population per unit area (Johnson & Cummings, 2013) which led to higher net loss.

4.2.3 Comparison Between Pericardial Injection and Dipping Tuber Seed Treatment Method

Even though pericardial injection contributed to higher yield compared to dipping which was also observed by Hollywood (2014), the latter had higher cost benefit ratio as a result of lower seed treatment labour than the former which was not established by the worker. Seed treatment through dipping method reduced the cost of seed treatment by 87.5%. Seed treatment by either dipping or pericardial injection contributed to disease management and improved yield and therefore cost benefit analysis was essential in determining the most cost effective method of seed treatment.

4.3 Estimation of Yield Increment

Tubers infected with late blight is of significant importance in potato production because they not only initiate early late blight epidemics and transmit the pathogen to sprouts, stems and foliage but also reduce yield quality and quantity. The infection result to death of sprouts reducing stem count or cause non-emergence resulting to poor and uneven stands due to seed decay causing reduced yield (Kirk & Samen, 2009). When weather conditions conducive to *P. infestans* are prolonged, the pathogen is translocated by wet film to other parts including stem resulting to wilting of the whole plant within 7 days (Whisson et al., 2016). Severe epidemics result to small tuber size affecting marketable grade which ultimately affect cost benefit (Bussan et al., 2007) as observed in unsprayed treatments. Fungicide application at 14 and 7 days effectively suppressed *P. infestans* while seed treatment with *T. asperellum* induced plant immunity offering prior protection which was reported by Komy et al. (2015). Early defoliation on unsprayed yet pre-treated plots led to failure to complete maximum tuberization and enlargement resulting to more unmarketable tubers. This finding confirms Yesuf and Desta (2015) findings who reported yield decline by 52.94% in unsprayed tomato due to defoliation by late blight. The observation was also in agreement with Deahl and Inglis (1993) findings who reported reduction in yield as a result of leaves loss. Leaves form a key component of photosynthesis and assimilation that contribute to yield formation. Yield increment by 10% was reported by Hijri (2016) when arbuscular mycorrhiza was inoculated on potato to improve on yield.

5. Conclusion and Recommendations

Late blight is a devastating disease causing significant yield loss if unchecked. In the present study, results suggests that seed treatment using either 66% and 100% was able to reduce early disease attack thereby increasing yield. 14 days interval was the best control in terms of disease management, yield and net benefits. Combination of *T. asperellum* concentration at 66% and 100% with Ridomil® application at 14 days was more beneficial not only in managing late blight but also in yield improvement. 21 days interval was ineffective in managing late blight. Untreated and seed treatment with 33% *T. asperellum* had similar yield and disease severity results. Even though yield of apical cuttings was similar to tuber seed crop during short rains, apical cuttings had a net loss. It was also observed that cost of seed takes over 80% of the total production indicating that much efforts should be geared towards improving tissue culture technology to enhance availability and affordability of seed. The findings suggest that combination of seed treatment with fungicide application is cost effective than fungicide application or seed treatment alone despite their additional costs. Seed treatment by dipping was more cost effective and could be adopted in offering seed with prior protection. The study attempted to solve latent infection on seed that initiate foliar and introduce soil borne pathogen inoculum affecting not only potato ware production but also seed production resulting to rejection of seed lot (Carroll et al., 2009). Biological control therefore is a promising tool in maintaining potato production levels while reducing environmental pollution. However, there is need to re-determine the cost benefit associated with apical cuttings against tuber as source of seed due to their higher generational level and cause for their vulnerability to late blight.

Acknowledgements

We would like to thank CESAAM EGERTON for funding this study and KALRO Tigoni Centre Director for providing laboratory, seed and field structures. Many thanks to REAL IPM Kenya for providing pure spores of *T. asperellum*. Thanks also to KALRO staff for their assistance during the study.

References

Abhiram, P., & Masih, H. (2018). *In vitro* antagonism of *Trichoderma viride* against *Fusarium oxysporum* strains. *Journal of Pharmacognosy and Phytochemistry, 7*(2), 2816-2819.

Akhtar, M. S., & Siddiqui, E. Z. A. (2008). *Glomus intraradices, Pseudomonas alcaligenes*, and *Bacillus pumilus*: effective agents for the control of root-rot disease complex of chickpea (*Cicer arietinum* L.). *Journal of General Plant Pathology, 74*, 53-60. https://doi.org/10.1007/s10327-007-0062-4

Andreu, A. B., & Caldiz, D. O. (2006). Early management of late blight (*Phytophthora infestans*) by using systemic fungicides applied to seed-potato tubers. *Crop Protection, 25*(3), 281-286. https://doi.org/10.1016/j.cropro.2005.05.002

Atkinson, M., & Parker, V. A. (2018). *Rooted apical cuttings to boost potato Seed Systems in Kenya*. International Potato Center, Lima, Peru.

Basahi, M. (2014). *Seed tuber treatments with Pseudomonas spp. to reduce potato common scab incidence and severity*. The University of Western OntarioLondon, Ontario, Canada.

Bengtsson, T., Holefors, A., Witzell, J., Andreasson, E., & Liljeroth, E. (2014). Activation of defence responses to *Phytophthora infestans* in potato by BABA. *Plant Pathology, 63*(1), 193-202. https://doi.org/10.1111/ppa.12069

Benz, J. S., Keller, E. R., & Midmore, D. J. (1995). Planting materials for warm tropic potato production: Growth and yield of transplanted seedlings or rooted cuttings and tuber materials in the field. *Field Crops Research, 40*, 179-192.

Bussan, A. J., Mitchell, P. D., Copas, M. E., & Drilias, M. J. (2007). Evaluation of the eff ect of density on potato yield and tuber size distribution. *Crop Science, 47*(1), 2462-2472. https://doi.org/10.2135/cropsci2007.01.0026

Caldiz, D. O., Rolon, D. A., & Rico, J. D. (2007). Performance of Dimethomorph+ Mancozeb applied to seed potatoes in early management of late blight (*Phytophthora infestans*). *Potato Research Journal, 50*, 59-70.

Carrero-carr, I., Monte, E., Hermosa, R., & Jim, R. M. (2016). *Trichoderma asperellum* is effective for biocontrol of Verticillium wilt in olive caused by the defoliating pathotype of *Verticillium dahliae*. *Phytopathology, 88*, 45-52. https://doi.org/10.1016/j.cropro.2016.05.009

Carroll, M. W., Radcliffe, E. B., Macrae, I. V., Ragsdale, D. W., & Olson, K. D. (2009). Border treatment to reduce insecticide use in seed potato production: Biological, economic, and managerial analysis. *American Journal of Potato Research, 86*, 31-37. https://doi.org/10.1007/s12230-008-9058-7

Chaouch, K. (2016). Inhibitory activity of *Trichoderma viride* against *Phytophthora infestans* that affects the Spunta potato (*Solanum tuberosum* L.) variety. *African Journal of Microbiology Research, 10*(29), 1121-1127. https://doi.org/10.5897/AJMR2016.7980

CIMMYT. (1998). *From agronomic data to farmer recommendations: An economic training manual*. Mexico, DF.

Croft, M. M., Marshall, M. I., Odendo, M., Ndinya, C., Ondego, N. N., & Obura, P. (2017). Formal and informal seed systems in kenya: supporting indigenous vegetable seed quality formal and informal seed systems in kenya: Supporting indigenous vegetable seed quality. *The Journal of Development Studies, 1*(0), 1-18. https://doi.org/10.1080/00220388.2017.1308487

Deahl, K, & Inglis, D, D. (1993). Testing for resistance to metalaxyl in *Phytophthora infestans* isolates from northwestern Washington. *American Journal of Potato Research, 70*, 779-795.

Dersseh, W. M., Gebresilase, Y. T., & Schulte, P. O. (2016). The analysis of potato farming systems in Chencha, Ethiopia: Input, output and constraints. *American Journal of Potato Research, 93*, 436-447. https://doi.org/10.1007/s12230-016-9521-9

Devaux, A., Kromann, P., & Ortiz, O. (2014). Potatoes for sustainable global food security. *Potato Research, 57*(3), 185-199. https://doi.org/10.1007/s11540-014-9265-1

El-Helaly, M. (2012). Propagation of potato (*Solanum tuberosum* L.) by seedlings. *American-Eurasian Journal Agriculture and Environment Science, 12*(9), 1117-1121. https://doi.org/10.5829/idosi.aejaes.2012.12.09.1875

Fatima, K., Noureddine, K., Henni, J. E., & Mabrouk, K. (2015). Antagonistic effect of *Trichoderma harzianum* against *Phytophthora infestans* in the North-west of Algeria. *International Journal of Agronomy and Agricultural Research, 6*(4), 44-53.

Flannery, M.-L., Thorne, F. S., Kelly, P. W., & Mullins, E. (2004). An Economic cost-benefit analysis of gm crop cultivation an irish Case Study. *AgBioForum, 7*(4), 149-157.

Foley, J. A., Defries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., & Snyder, P. K. (2005). Global Consequences of Land Use: Review. *Science, 309*(5734), 570-575.

Forbes, G. A. (1997). *Manual for Laboratory Work on Phytophthora infestans CIP Training Manual*. International Potato Center, Lima, Peru.

Forbes, G. A. (2012). Using host resistance to manage potato late blight with particular reference to developing countries. *Potato Research, 55*, 205-216. https://doi.org/10.1007/s11540-012-9222-9

Forbes, G. A. (2013). *Using Host Resistance to Manage Potato Late Blight with Particular Reference to Developing Countries*. Lima, Peru. https://doi.org/10.1007/s11540-012-9222-9

Gao, L., & Bradeen, J. M. (2016). Contrasting potato foliage and tuber defense mechanisms against the late blight pathogen *Phytophthora infestans*. *PLoS ONE, 11*(7), 1-15. https://doi.org/10.1371/journal.pone.0159969

Gigot, J. A., Gundersen, B., & Inglis, D. A. (2009). Colonization and sporulation of *Phytophthora infestans* on volunteer potatoes under western Washington conditions. *American Journal of Potato Research, 86*(1), 1-14. https://doi.org/10.1007/s12230-008-9054-y

Gildemacher, P. R., Demo, P., Barker, I., Kaguongo, W., & Struik, P. C. (2009). A description of seed potato systems in Kenya, Uganda. *American Journal Potato Research, 86*, 373-382. https://doi.org/10.1007/s12230-009-9092-0

Gildemacher, P. R., Schulte, G. E., & Borus, D. (2011). Seed Potato Quality Improvement through Positive Selection by Smallholder Farmers in Kenya. *Potato Research, 54*, 253-266. https://doi.org/10.1007/s11540-011-9190-5

Godfray, H., & Charles, J. (2010). Food Security: The challenge of feeding 9 billion people. *Science, 327, 812*, 812-818. https://doi.org/10.1126/science.1185383

Guchi, E. (2015). Disease management practice on potato (*Solanum tuberosum* L.) in Ethiopia. *World Journal of Agricultural Research, 3*(1), 34-42. https://doi.org/10.12691/wjar-3-1-8

Halloran, J. M., Larkin, R. P., Defauw, S. L., Olanya, O. M., & He, Z. (2013). Economic potential of compost amendment as an alternative to irrigation in maine potato production. *American Journal of Plant Science, 4*, 238-245. https://doi.org/10.4236/ajps.2013.42031

Hermosa, R., Cardoza, R. E., Gutie, S., & Monte, E. (2011). Functional analysis of the *Trichoderma harzianum* nox1 Gene, Encoding an NADPH Oxidase, relates production of reactive oxygen species to specific biocontrol activity against *Pythium ultimum*. *Applied and Environmental Microbiology, 77*(9), 3009-3016. https://doi.org/10.1128/AEM.02486-10

Hijri, M. (2016). Analysis of a large dataset of mycorrhiza inoculation field trials on potato shows highly significant increases in yield. *Mycorrhiza, 26*(1), 209-214. https://doi.org/10.1007/s00572-015-0661-4

Hollywood, J. C. (2014). *Biological Control of Late Blight of Potatoes: in vivo and in vitro evaluation of microbial antagonists against tuber blight* (PhD Thesis, University of Bristol, UK).

Hu, C., Pathology, P., Carolina, N., Perez, F. G., States, U., Roberts, P. D., & Ristaino, J. B. (2012). Recent genotypes of *Phytophthora infestans* in the Eastern United States reveal clonal populations and reappearance of mefenoxam sensitivity. *Plant Disease, 96*, 1323-1330.

Itachi, T. M., Anamori, M. K., Eraoka, T. T., & Rie, T. A. (2007). Mode of action of *Trichoderma asperellum* SKT-1, a biocontrol agent against *Gibberella fujikuroi*. *Journal of Pesticide Science, 32*(3), 222-228. https://doi.org/10.1584/jpestics.G06-35

Jaetzold, R., Schmidt, H., Hornetz, B., & Shisanya, C. (2006). *Farm management handbook of Kenya-Natural conditions and farm management information* (2nd ed., Volume II/B). Ministry of Agriculture, Nairobi.

Janzen, H. H. (2011). Global prospects rooted in soil science food: How can we feed billions more without harming our soil. *Soil Science Society American Journal, 75*(1), 1-8. https://doi.org/10.2136/sssaj2009.0216

Jiang, H. H., Ge, T. L., Zhang, X. M., Marangoni, N., Giggie, E., & Hao, J. J. (2017). Effects of Revus as a seed treatment for control of seedborne late blight and pink rot. *Plant Disease Management Reports, 11*, ST004.

Johnson, D. A., & Cummings, T. F. (2013). A plant stem inoculation assay for assessing transmission of *Phytophthora infestans* from potato seed tubers to emerged shoots. *Plant Disease, 97*(2), 183-188. https://doi.org/10.1094/PDIS-06-12-0561-RE

Kamoun, S., Furzer, O., Jones, J. D. G., Judelson, H. S., Ali, G. U. L. S., Dalio, R. J. D., & Govers, F. (2015). The Top 10 oomycete pathogens in molecular plant pathology. *Molecular Plant Pathology, 16*, 413-434. https://doi.org/10.1111/mpp.12190

Kamoun, S., Furzer, O., Jones, J. D. G., Judelson, H. S., Ali, G. U. L. S., Dalio, R. J. D., … Govers, F. (2015). The Top 10 oomycete pathogens in molecular plant pathology. *Molecular Plant Pathology, 16*, 413-434. https://doi.org/10.1111/mpp.12190

Kassa, B., & Beyene, H. (2001). Efficacy and economics of fungicide spray in the control of late blight of potato in Ethiopia. *African Crop Science Journal, 9*(1), 245-250.

Keswani, C., Singh, S. P., & Singh, H. B. (2014). A superstar in biocontrol enterprise: *Trichoderma* spp. *Biotechnology Today, 3*(2), 3-6. https://doi.org/10.5958/2322-0996.2014.00005.2

Kirk, W. W., & Samen, F. A. (2009). Impact of different us genotypes of *Phytophthora infestans* on Potato seed tuber rot and plant emergence in a range of cultivars and advanced breeding lines. *Potato Research, 40*, 121-140. https://doi.org/10.1007/s11540-009-9125-6

Kirk, W. W., Pathology, P., Felcher, K. J., Douches, D. S., Coombs, J., Sciences, S., & Baker, K. M. (2001). Effect of host plant resistance and reduced rates and frequencies of fungicide application to control potato late blight. *Plant Biology, 85*(1), 1113-1118.

Kirk, W. W., Rojas, A., Tumbalam, P. G., Gachango, E., Wharton, P. S., El-samen, F. A., & Coombs, J. (2010). Effect of different genotypes of *Phytophthora infestans* (Mont. de Bary) and temperature on tuber disease development. *American Journal of Potato Research, 87*, 509-520. https://doi.org/10.1007/s12230-010-9156-1

Kohl, J., Kolnaar, R., & Ravensberg, W. J. (2019). Mode of action of microbial biological control agents against plant diseases: Relevance beyond efficacy. *Frontiers in Plant Science, 10*(845), 1-19. https://doi.org/10.3389/fpls.2019.00845

Komy, M. H. El-Saleh, A. A., Eranthodi, A., & Molan, Y. Y. (2015). Characterization of novel T*richoderma asperellum* isolates to select effective biocontrol agents against tomato fusarium wilt. *Plant Pathology Journal, 31*(1), 50-60.

Kumar, S., Thakur, M., & Rani, A. (2015). *Trichoderma*: Mass production, formulation, quality control, delivery and its scope in commercialization in India for the management of plant diseases. *African Journal of Agricultural Research, 9*(53), 3838-3852. https://doi.org/10.5897/AJAR2014

Laila, N., Yusuf, U., Ismail, A., & Hossain, K. (2014). *Trichoderma* spp.: A biocontrol agent for sustainable management of plant diseases. *Pakistan Journal of Botany, 46*, 1489-1490.

Liljeroth, E., Lankinen, Å., Wiik, L., Burra, D. D., Alexandersson, E., & Andreasson, E. (2016). Potassium phosphite combined with reduced doses of fungicides provides efficient protection against potato late blight in large-scale field trials. *Crop Protection, 86*, 42-55. https://doi.org/10.1016/j.cropro.2016.04.003

Lobell, D. B., Cassman, K. G., Field, C. B., & Field, C. B. (2009). Crop Yield Gaps: Their Importance, magnitudes, and causes crop yield gaps: Their importance, magnitudes, and causes. *Annual Review of Environment and Resources, 34*, 179-204. https://doi.org/10.1146/annurevfienviron.041008.093740

López-Bucio, J., Pelagio-Flores, R., & Herrera-Estrella, A. (2015). *Trichoderma* as biostimulant: Exploiting the multilevel properties of a plant beneficial fungus. *Scientia Horticulturae, 196*, 109-123. https://doi.org/10.1016/j.scienta.2015.08.043

Majeed, A., Muhammad, Z., Ullah, Z., Ullah, R., & Ahmad, H. (2017). Late Blight of Potato (*Phytophthora infestans*) I: Fungicides Application and Associated Challenges. *Turkish Journal of Agriculture-Food Science and Technology, 5*(3), 261-266. https://doi.org/10.24925/turjaf.v5i3.261-266.1038

Miles, L. A., Lopera, C. A., Gonza, S., Franco, A. E., & Restrepo, S. (2012). Exploring the biocontrol potential of fungal endophytes from an Andean Colombian Paramo ecosystem. *Biocontrol, 57*(5), 697-710. https://doi.org/10.1007/s10526-012-9442-6

Mosota, E. L., Kange, A. M., Wati, L. N., & Otaye, D. O. (2017). Effects of Fertilizer and Fungicide Application Rates on the Incidence and Severity of Late Blight (*Phytophthora infestans*) on Irish Potatoes (*Solanum tuberosum*. *World Journal of Agricultural Research, 5*(3), 169-176.

Muchiri, F. N., Narla, R. D., Olanya, O. M., Nyankanga, R. O., & Ariga, E. S. (2017). Efficacy of fungicide mixtures for the management of *Phytophthora infestans* (US-1) on potato. *Phytoprotection, 90*, 19-29. https://doi.org/10.7202/038983ar

Murasnige, T. (1962). A revised medium for rapid growth and bio agsays with tohaoco tissue cultures. *Physiologia Plantarum, 15*, 473-497.

Muthoni, J., Mbiyu, M. W., & Nyamongo, D. O. (2017). A Review of Potato Seed Systems and Germplasm Conservation in Kenya. *Journal of Agricultural Science and Information, 11*(2), 157-167. https://doi.org/10.1080/10496501003680565

Nærstad, R., Hermansen, A., & Bjor, T. (2007). Exploiting host resistance to reduce the use of fungicides to control potato late blight. *Plant Pathology, 56*(1), 156-166. https://doi.org/10.1111/j.1365-3059.2006.01491.x

Namanda, S., Olanya, O. M., Adipala, E., Hakiza, J. J., & El-bedewy, R. (2004). Fungicide application and host-resistance for potato late blight management: Benefits assessment from on-farm studies in S.W. Uganda. *Crop Protection, 23*, 1075-1083. https://doi.org/10.1016/j.cropro.2004.03.011

Norkotah, R. (2002). Assessment of the impact of mid-season late blight infection on disease development and yield of potato variety Russet Norkotah in Maine. *International Journal of Pest Management, 48*(2), 139-147. https://doi.org/10.1080/09670870110102594

Olanya, O. M., Ojiambo, P. S., Ewell, P. T., & Hakiza, J. J. (2001). Relationships of Fungicide Application to Late-Blight Development and Potato Growth Parameters in the Tropical Highlands of Uganda and Kenya. *International Journal of Pest Management, 39*(2), 139-147.

Pule, B. B., Meitz, J. C., Thompson, A. H., Linde, C. C., Fry, W. E., Langenhoven, S. D., & Rij, N. C. (2013). *Phytophthora infestans* populations in central, eastern and southern African countries consist of two major clonal lineages. *Plant Pathology, 62*, 154-165. https://doi.org/10.1111/j.1365-3059.2012.02608.x

Qiu, Z., Wu, X., Zhang, J., & Huang, C. (2017). High temperature enhances the ability of *Trichoderma asperellum* to infect *Pleurotus ostreatus* mycelia. *PLoS ONE, 12*(10), 1-16. https://doi.org/10.1371/journal.pone.0187055

Redda, E. T., Ma, J., Mei, J., Li, M., Wu, B., & Jiang, X. (2018). Antagonistic potential of different isolates of *Trichoderma* against fusarium. *European Journal of Experimental Biology, 8*(2), 1-8. https://doi.org/10.21767/2248-9215.100053

Rekanović, E., Potočnik, I., Milijašević-marčić, S., & Stepanović, M. (2011). Sensitivity of *Phytophthora infestans* (Mont.) de bary Isolates to Fluazinam, Fosetyl-Al and Propamocarb-hydrochloride. *Pesticide Phytomed, 26*(2), 111-116. https://doi.org/10.2298/PIF1102111R

Savary, S., Ficke, A., Aubertot, J., & Hollier, C. (2012). Crop losses due to diseases and their implications for global food production losses and food security. *Food Security, 4*(4), 519-537. https://doi.org/10.1007/s12571-012-0200-5

Sharma, P., & Saikia, M. K. (2013). Management of late blight of potato through chemicals. *IOSR Journal of Agriculture and Veterinary Science, 2*(2), 23-26.

Siddique, N. A., Aktar, M. S., & Swapon, N. (2016). Comparative Efficacy of Different Fungicides against Late Blight Diseases of Potato incited by *Phytophthora infestans* (Mont.) de Bary and its Management. *Journal of Plant Pathology and Microbiology, 7*(7), 364-370. https://doi.org/10.4172/2157-7471.1000364

Somani, A. K., & Arora, R. K. (2010). Field efficacy of *Trichoderma viride, Bacillus subtilis* and *Bacillus cereus* in consortium for control of *Rhizoctonia solani* causing black scurf disease of potato. *Indian Phytopathology, 63*(1), 23-25.

Syed, S. F., Singh, E., Pieterse, C. M. J., & Schenk, P. M. (2018). Emerging microbial biocontrol strategies for plant pathogens. *Plant Science, 267*, 102-111. https://doi.org/10.1016/j.plantsci.2017.11.012

Tadesse, S. M., & T. (2018). Effect of varieties and fungicides on potato late blight (*Phytophthora infestans*). *Agrotechnology, 7*(2), 2-5. https://doi.org/10.4172/2168-9881.1000182

Taylor, P., Nyankanga, R. O., Wien, H. C., Olanya, O. M., & Ojiambo, P. S. (2013). Farmers ' cultural practices and management of potato late blight in Kenya Highlands: implications for development of integrated disease management. *International Journal of Pest Management, 50*(2), 37-41. https://doi.org/10.1080/09670870410001691812

Viterbo, A., Landau, U., Kim, S., Chernin, L., & Chet, I. (2010). Characterization of ACC deaminase from the biocontrol and plant growth-promoting agent *Trichoderma asperellum* T203. *FEMS Microbiology Letter, 305*, 42-48. https://doi.org/10.1111/j.1574-6968.2010.01910.x

Wharton, P. S., Kirk, W. W., Berry, D., & Tumbalam, P. (2007). Seed treatment application-timing options for control of Fusarium decay and sprout rot of cut seed pieces. *American Journal of Potato Research, 87*, 237-244.

Wharton, P. S., Kirk, W. W., Schafer, R. L., & Tumbalam, P. (2012). Evaluation of biological seed treatments in combination with management practices for the control of seed-borne late blight in potato. *Biological Control, 63*, 326-332.

Whisson, S. C., Boevink, P. C., Wang, S., & Birch, P. R. J. (2016). The cell biology of late blight disease. *Current Opinion in Microbiology, 34*, 127-135. https://doi.org/10.1016/j.mib.2016.09.002

Wu, F., Wang, W., Ma, Y., Liu, Y., Ma, X., & An, L. (2013). Prospect of beneficial microorganisms applied in potato cultivation for sustainable agriculture. *African Journal of Microbiology Research, 7*(20), 2150-2158. https://doi.org/10.5897/AJMRx12.005

Wu, Y., Jiang, J., & Gui, C. (2012). Low genetic diversity of *Phytophthora infestans* population in potato in north China. *African Journal of Microbiology Research, 11*(90), 15636-15642. https://doi.org/10.5897/AJB12.484

Xu, X., Jeffries, P., Pautasso, M., & Jeger, M. J. (2011). Combined Use of Biocontrol Agents to Manage Plant Diseases in Theory and Practice. *Phytopathology, 101*, 1024-1031.

Yao, Y., Li, Y., Chen, Z., Zheng, B., Zhang, L., Niu, B., & Wang, Q. (2016). Biological control of potato late blight using isolates of *Trichoderma. American Journal of Potato Research, 93*(1), 33-42. https://doi.org/10.1007/s12230-015-9475-3

Yesuf, M. D., & M. (2015). Efficacy and Economics of Fungicides and their Application Schedule for early blight (*Alternaria solani*) management and yield of tomato. *Journal of Plant Pathology and Microbiology, 6*(5). https://doi.org/10.4172/2157-7471.1000268

Yuen, J. E., & Forbes, G. A. (2009). Estimating the level of susceptibility to *Phytophthora infestans* in potato genotypes. *Phytopathology, 99*, 782-786.