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EFFECT OF INTERCROPPING ON POTATO BACTERIAL WILT DISEASE AND TUBER YIELD IN KENYA

S.M. MUSAH[1, 3], R.K. BIRITHIA[2], H.W. KAMIRI[2] and E. KAHARIRI[3]

[1]Ministry of Agriculture, Livestock and Fisheries, P. O. Box 2870-20100, Nakuru, Kenya
[2]School of Agriculture and Biotechnology, P. O. Box 1957-10101, Karatina, Kenya
[3]School of Pure and Applied Sciences, P. O. Box 1957-10101, Karatina, Kenya
Corresponding author: msmatika@yahoo.com

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ABSTRACT

Potato (*Solanum tuberosum* L.) is a major tuber crop in Kenya, whose productivity is heavily impaired by bacterial wilt disease, caused by *Ralstonia solanacearum* (Smith). Existing management strategies have not been effective, owing to the diversity and robustness of the pathogen and variation in the host range. The objective of this study was to evaluate the effectiveness of intercropping on the incidence of bacterial wilt and yield of potato in Kenya. A field experiment was conducted in four potato-growing counties, namely; Nyandarua, Nakuru, Bomet and Bungoma in Kenya. Treatments included intercroping with spring onion (*Allium fistulosum* L.); garden pea (*Pisum sativum* L.); and cabbage (*Brassica oleracea* var. capitata L.). Treatments also included a pure stand of potato as the control. Generally, intercropping had a significant suppressive effect ($P<0.05$) on the incidence and severity of bacterial wilt disease. Intercropping potato with spring onion, in particular, had the highest disease suppressive effect, followed by intercropping potato with cabbage; and lastly by potato with garden pea. Accordingly, potato-onion intercrop recorded the highest potato tuber yield (12.9 t ha^{-1}), while the potato pure stand recorded the lowest tuber yield (7.9 t ha^{-1}). Bacterial wilt disease incidence positively correlated with disease severity ($r = 0.931$; $P<0.05$). In contrast, the disease incidence and severity negatively correlated with tuber yield. In terms of Land Equivalent Ratio (LER), the highest value (1.64) was with potato-onion intercrop; and the lowest (1.35) with the potato-garden pea intercrop.

Key Words: Cabbage, *Ralstonia solanacearum, Solanum tuberosum.*

RÉSUMÉ

La pomme de terre (*Solanum tuberosum* L.) est une culture de tubercule majeure au Kenya, dont la productivité est fortement altérée par le flétrissement bactérien provoqué par *Ralstonia solanacearum* (Smith). Les stratégies de gestion existantes n'ont pas été efficaces, en raison de la diversité et de la robustesse de l'agent pathogène et de la variation de la gamme d'hôtes. L'objectif de cette étude était d'évaluer l'efficacité des cultures intercalaires sur l'incidence du flétrissement bactérien et le rendement de la pomme de terre au Kenya. Une expérience sur le terrain a été menée dans quatre comtés producteurs de pommes de terre, à savoir : Nyandarua, Nakuru, Bomet et Bungoma au Kenya. Les traitements comprenaient la culture intercalaire avec de la ciboule (*Allium fistulosum* L.) ; pois de jardin (*Pisum sativum* L.); et le chou (*Brassica oleracea* var. capitata L.). Les traitements comprenaient également un peuplement pur de pomme de terre comme témoin. En général, les cultures intercalaires ont eu un effet suppresseur significatif (P < 0,05) sur l'incidence et la gravité du flétrissement bactérien. La culture intercalaire de pommes de terre avec de l'oignon nouveau, en particulier, a eu l'effet suppresseur de maladie le plus élevé, suivie par la culture intercalaire de pommes de terre avec du chou ; et enfin de la pomme de terre aux petits pois. Ainsi, la culture associée pomme de terre- ciboule a enregistré le rendement en tubercules de pomme de terre le plus élevé (12,9 t ha^{-1}), tandis que le peuplement pur de pomme de terre a enregistré le rendement en tubercules le plus faible (7,9 t ha^{-1}). L'incidence de la flétrissure bactérienne était positivement corrélée à la gravité de la maladie (r = 0,931 ; P < 0,05). En revanche, l'incidence et la gravité de la maladie étaient négativement corrélées au rendement en tubercules. En termes de ratio d'équivalent terre (RET), la valeur la plus élevée (1,64) concernait la culture intercalaire pomme de terre- ciboule; et le plus bas (1,35) avec la culture intercalaire pomme de terre-pois de jardin.

Mots Clés : Chou, *Ralstonia solanacearum, Solanum tuberosum*

INTRODUCTION

Potato (*Solanum tuberosum* L.) cultivation in Kenya has shown positive trends, although the country continues to record low yields of up to 10 t ha^{-1}, against the potential of 40 t ha^{-1}, achievable under the recommended agronomic practices (FAOSTAT, 2017; NPCK, 2019). This is largely attributed to devastating diseases such as bacterial wilt caused by *Ralstonia solanacearum* (Smith) (Ahmad and Elizabeth, 2018; Osdaghi, 2021).

Globally, the disease has been estimated to affect about 1.7 million hectares of potatoes in approximately 80 countries, with global damage estimates of over US$ 950 million per *annum* (Florence *et al.,* 2018; Karim *et al.*, 2018). The disease is found in all potato growing areas in Kenya, affecting over 77% of potato farms, with estimated yield losses of up to 70% (Ong'au *et al.*, 2021).

Control of bacterial wilt disease mainly relies on the use of soil fumigants, host plant resistance, disease-free planting materials, crop rotation and sanitation measures (Yuliar and Koki, 2015). However, these control strategies have not been effective, owing to the diversity of pathogens, characterised by several strains that differ in host range, geographical distribution and pathogenicity (Prior *et al.*, 2016; Santiago *et al.*, 2016). Moreover, fumigants are hazardous to humans and to the environment (Yuliar and Koki, 2015).

Although resistance breeding offers the first line of defence against plant pathogens, it is only successful against race 1 of the pathogen in tropical crops like eggplant, tomato, peanut, pepper and to a very small extent on potato in South America (Muthoni *et al.*, 2014). Thus, there is an urgent need for an integrated management approach encompassing cultural control practices such as crop rotation, and delayed planting or intercropping, all of which are eco-friendly and non-hazardous to man (Kurabachew and Ayana, 2017).

Intercropping, which is an agricultural practice in which two or more crops are grown together in the field at the same time, has been used throughout history in the management of plant diseases (Luo *et al.*, 2021). Studies have demonstrated that intercropping increases crop productivity, as well as suppresses of soil-borne diseases, when compared to mono-culture systems (Tanveer *et al.,* 2017; Du *et al.*, 2018; Chang *et al.*, 2020). Recent studies have shown that intercropping enhances the resistance of watermelon to *Fusarium wilt* in wheat/ watermelon intercrops; and reduces the occurrence of *Phytophthora blight* of pepper in maize/pepper intercrops (Yang *et al*., 2014; Lv *et al*., 2018). Further studies have shown that maize/soybean relay strip intercropping significantly reduces occurrence of *Fusarium* root rot in soybean (Chang *et al.,* 2022)

Despite the extensive use of intercrops in the management of soil-borne bacterial and fungal diseases, information on the application of this technology to control potato bacterial wilt in Kenya is lacking. The objective of this study was to evaluate the effectiveness of intercropping on incidence of bacterial wilt and yield of potato in Kenya.

MATERIALS AND METHODS

Study sites. This study was conducted in four major potato producing counties of Nyandarua, Bomet and Nakuru, and Bungoma in Kenya. Climatic and edaphic characteristics of these sites are presented in Table 1. Two wards in each county and five farmers' fields from each ward were selected for the bacterial wilt field survey, before narrowing down on sites for the field experiment.

Experimental procedure. Study site land was prepared to the desired tilth and subdivided into plots measuring 3 m x 3.3 m. The plots and blocks were separated by respective distances of 1 m and 2 m. Potato tubers (*Shangi* variety) were planted at a spacing of 90 cm between rows and 30 cm within rows. Treatments included three intercrops, namely, potato-spring onion (var. green bunching), potato-garden pea (variety pea's plum) and potato-cabbage (var. *Copenhagen*). This was done in alternating two potato rows to one row of the other intercrop component.

The experiment was laid out in a Randomised Complete Block Design (RCBD) design, in split plot arrangement. The main plot treatment was the inoculum level; while the sub-plot treatment was intercropping regime. The setup was replicated four times in naturally infested bacterial wilt fields. The study was conducted for two rainy seasons, April-July 2019 and September-December 2019. The study setup was generally rain-fed and supplemented with irrigation during the dry seasons.

Drainage furrows were dug between plots and blocks to prevent surface runoff and its cross-contamination of the plots. Di-ammonium phosphate (18-46-0) fertiliser was applied as a baseline, at the rate of 200 kg ha^{-1}, at planting. Additionally, all plots were top-dressed with 100 kg ha^{-1} calcium ammonium nitrate (26% N) at 45 days after planting.

Early blight (*Alternaria solani* (Ellis & Martin) Sorauer and late blight (*Phytophthora infestans* (Mont.) de Barry, diseases in the intercrop were controlled by spraying using Ridomil 68 WG (Metalaxyl 40 g kg^{-1} and Mancozeb 640 g kg^{-1}), at the rate of 2 kg ha^{-1} at 21 day-spray interval between two fungicide sprays. Sucking pests, including aphids and whiteflies were controlled by spraying the seedling with Actara 25 WG (Thiamethoxam 25%), at the rate of 0.5 kg ha^{-1}. Weeding was done twice at 21 and 45 days, after potato emergence.

Data collection. Bacterial wilt infection was assessed for six weeks at intervals of 7 days, starting from the onset of the first wilt symptoms. At each assessment, all plants that showed either complete or partial wilting were considered wilted. These plants were staked to avoid double counting in subsequent assessments; and also to avoid the possibility of missing those that die off completely during the growth period. Bacterial wilt disease incidence was determined by dividing the number of infected plants by the total number of observed plants (Equation 1).

$$\text{Bacterial wilt disease incidence (\%)} = \frac{\text{Number of infected plants per plot x 100}}{\text{Total plants per plot}} \quad \text{........................ Equation 1}$$

A disease severity score scale of 1-5 as described by Horita and Tsuchiya (2001) was used;

TABLE 1. Climatic and edaphic characteristics of experimental sites

County	Specific location/ ward	GPS coordinates	Average rainfall (mm)	Average temperature ^{0}C	Soil type	PH
Nyandarua	Milangine	2515 m asl S 00^{o}17.440 and E 036^{o}16.401	1800	16	Clay loam Humic nitisol	4.5-5.5
Nakuru	Elburgon	2502 m asl S 00^{o}17.696 and E 035^{o}46.071	1750	16	Sandy loam Mollic Andosols	4.0-5.5
Bomet	Silibwet	2045 m asl S 00^{o}51.350 and E 035^{o}23.280	1247	18	Sandy loam Humic Natisols	4.5-5.5
Bungoma	Elgon	1941 m asl N 00^{o}50.455 and E 034^{o}41.576	1530	18	Sandy loam Dystric-Mollic Natisol	4.5-5.5

Source: Jaetzold and Schmidt (2006); Mwaniki (2019)

Where:

1 = no symptom;
2 = minor damage (10- 30% leaf damage);
3 = moderate damage (31- 50% leaf damaged);
4 = severe damage (51- 75% leaf damaged); and
5 = total crop damage (76-100% leaf damaged.

The disease severity scores recorded were used to estimate the area under the disease progression curve (AUDPC). The severity was converted into percentage severity indices (PSI) for analysis. This was done by dividing the sum of numerical ratings by the number of plants scored multiplied by the maximum score on the scale (5). The disease progress rate (r) and area under the disease progress curve (AUDPC) were calculated from the severity data. AUDPC was computed from PSI data calculated every week as described by Aguk *et al*. (2018).

Harvesting of the tubers was done at 110 days after planting; when more than 75% of the plants had reached senescence. At harvesting, total and marketable tuber yields were separately determined. Since latent bacterial wilt infection was not tested on the harvested tubers in this experiment, the yield reported is for ware potatoes.

Computation of Land Equivalent Ratio (LER). Land Equivalent Ratios (LERs) for the different cropping regimes were computed using Equation 2 (Mugisa *et al.*, 2020);

$$LER = \frac{Y\ intercrop\ 1 + Y\ intercrop\ 2}{Y\ monocrop\ 1 + Y\ monocrop\ 2} \qquad \text{Equation 2}$$

Where:

Y = the yield per unit area of either crop 1 or crop 2 in either monoculture or intercrop.

Land Equivalent Ratio (LER) = (1) partial land equivalent ratio for potato (PLER P) + partial land equivalent ratio for onions (PLER O), (2) partial land equivalent ratio for potato (PLER P) + partial land equivalent ratio for cabbage (PLER C), and (3) partial land equivalent ratio for potato (PLER P) + partial land equivalent ratio for garden peas (PLER G).

Where:

Partial Land Equivalent Ratio for Potato (PLER P) = yield of potato when intercropped with onions divided by yield of sole potato;

Partial Land Equivalent Ratio for onions (PLER O) = yield of onions when intercropped with potato divided by yield of sole onions;

Partial Land Equivalent Ratio for cabbage (PLER C) = yield of cabbages when intercropped with potato divided by yield of sole cabbages;

Partial Land Equivalent Ratio for garden peas (PLER G) = yield of garden peas when intercropped with potato divided by yield of sole garden peas.

Partial Land Equivalent Ratio values of less than 1 show no yield advantage from the intercrops, but rather a negative effect on crop yield.

The LER greater than 1 indicates a yield advantage of intercropping compared to monocropping.

Data analysis. Data collected were subjected to Analysis of variance (ANOVA) using the General linear model (GLM) procedure of SAS, 2005 version 9.1 (SAS, 2005). Significant treatment means were separated using the Least Significance Difference Test at a 5% level of significance. Pearson correlation was done among the variables.

RESULTS

Disease incidence and severity. Table 2 presents evidence of significant differences ($P<0.05$) in disease incidence among the intercrops and sites. At Bomet site, potato-onion intercrop recorded the lowest disease incidence (33.1%); while the pure potato stand resulted in the highest disease incidence value of 63.6 % in Nakuru. (Table 2).

Disease severity was significantly different across treatments and sites (Table 3). The highest disease severity score (3.3) was recorded in potato monocrop at all sites. Nakuru recorded the highest severity score (3.9) in potato monocrop; while the lowest (2.2) was recorded in potato-onion intercrop at Nakuru site. At Bomet the lowest severity score (1.9) was recorded in the potato-onion intercrop; which was not significantly lower

TABLE 2. Effect of intercropping on bacterial wilt disease incidence in selected potato growing regions in Kenya

Cropping regime	Nyandarua	Nakuru	Bomet	Bungoma	Mean
P+O	43.8a*	48.9a	33.1a	35.3a	40.3a
P+C	45.3b	51.3ab	36.9b	38.7b	43.0b
P+GP	51.7c	53.3b	42.6c	41.3c	47.3c
P mono	59.8d	63.6c	51.6d	52.7d	56.9d
LSD	1.28	2.84	2.43	2.01	1.55
CV%	1.97	4.03	4.57	3.69	2.55
F value	217.94	35.04	73.54	94.81	148.49
P value	.000001	.00014	.000007	.000005	.0000002

* Means in the same column followed by the same letter (a, b, c) are not significantly different using Least significance difference (LSD) test, $\alpha = 0.05$. P+O =Potato intercropped with onion, P+C= Potato intercropped with cabbage, P+GP= Potato intercropped with garden peas, P mono = Potato mono crop

TABLE 3. Effect of intercropping on bacterial wilt severity in selected potato growing regions in Kenya

Cropping regime	Nyandarua	Nakuru	Bomet	Bungoma	Mean severity
P+O	2a*	3a	1.8a	2.1a	2.2a
P+C	2.1ab	3a	1.9a	2.3a	2.3a
P+GP	2.5b	3.2a	2.4b	2.7b	2.7b
P mono	3.2c	3.9b	2.8c	3.2c	3.3c
LSD	0.42	0.24	0.36	0.36	0.12
CV%	13.28	5.63	12.55	10.81	3.6
F value	9.84	24.18	11.70	12.79	100.90
P value	.00335	.99158	.00186	.00135	<.00001

* Means in the same column followed by the same letter (a, b, c) are not significantly different using Least significance difference (LSD) test, $\alpha = 0.05$. P+O=Potato intercropped with onion, P+C= Potato intercropped with cabbage, P+GP= Potato intercropped with garden peas, P mono= Potato mono crop

(P>0.05) than the potato-cabbage intercrop. Notably, there was no significant difference (P>0.05) in bacterial wilt disease severity in potato-onion and potato-cabbage intercrop in both experimental sites (Table 3).

In Nakuru, although potato-onion intercrop maintained the lead in suppressing the disease incidence, this treatment was not significantly different (P>0.05) from that of potato-cabbage intercrop (Table 4).The reduction in bacterial wilt disease incidence was significantly different across treatments and sites (Table 4).The highest reduction in bacterial wilt disease incidence score of 35.88% was recorded in potato/onion intercrop in Bomet. This was followed by Bungoma with a score of 33% (Table 4). The lowest reduction of 13.45% was recorded in potato-garden pea intercrop in Nyandarua which was followed by 16.19% in Nakuru.

The highest reduction in bacterial wilt severity was recorded in potato-onion intercrop in Nyandarua with a score of 37.5% (Table 4) which was closely followed by a reduction of 35.71% in Bomet. The lowest reduction in disease severity was recorded in potato-garden pea intercrop in Bomet with a score of 14.29% which was followed by 15.63% reduction in Bungoma.

Area under disease progress curve (AUDPC). Potato monocrop recorded the highest AUDPC of 1821.4, which was significantly greater (P<0.05) than the other cropping regimes. The lowest mean AUDPC of 1001.2 was recorded in potato-onion intercrop, which was not significantly lower (P>0.05) than that of the potato-cabbage intercrop; which was closely followed by potato-garden pea intercrop (Table 5). Potato-onion intercrop reduced AUDPC by 54.21% in Nakuru, which was closely followed by 52.8% reduction in Bomet. The lowest AUDPC of 15.26% was recorded in potato-garden pea intercrop in Nakuru.

Potato tuber yield. There was a significant intercrop effect of potato tuber yield a cross all treatments, but not sites (Table 6). In all the study sites, the highest potato yield was recorded in potato-onion intercrop with mean yield of 12.9 t ha^{-1} (Table 6). Bomet recorded the highest potato tuber yield of 16.6 t $ha^{-1}$for potato-onion intercrop regime. This was closely followed by potato-cabbage intercrop across all sites with mean yield of 11.9 t ha^{-1} and in turn by potato-garden pea intercrops with mean of 10.8 t ha^{-1}. Potato monocrop

TABLE 4. Effect of intercropping on Area under disease progress curve (AUDPC) in selected potato growing counties in Kenya

Cropping regime	Nyandarua	Nakuru	Bomet	Bungoma	Mean AUDPC
P+O	882.7	1454.4	709.5	958.1	1001.2a
P+C	966.9	1525	771.6	1218.9	1120.6a
P+GP	1108.8	1703.1	1139.5	1773.1	1431.1b
P mono	1508.3	2181.9	1503.1	2092.5	1821.4c
LSD					163.91
CV %					9.41
F value					33.59
P value					0.00003

* Means in the same column followed by the same letter (a, b, c, d) are not significantly different using Least significance difference (LSD) test, $\alpha = 0.05$. P+O=Potato intercropped with onion, P+C= Potato intercropped with cabbage, P+GP= Potato intercropped with garden peas, P mono= Potato mono crop

TABLE 5. Effect of intercropping on mean percentage reduction of bacterial wilt incidence, severity and AUDPC in potato growing regions in Kenya

Cropping regime	Nyandarua	Nakuru	Bomet	Bungoma	Mean
Incidence					
P+O	26.73	23.18	35.88	33	29.26
P+C	24.31	19.46	28.46	26.59	24.38
P+GP		13.45	16.19	17.34	21.59
16.98					
Severity					
P+O	37.5	23.08	35.71	34.38	32.06
P+C	34.38	23.08	32.14	28.13	29
P+GP	21.88	17.95	14.29	15.63	17.56
AUDPC					
P+O	33.34	54.21	52.80	41.48	45.03
P+C	30.11	41.75	48.67	35.9	38.48
P+GP	21.94	15.26	24.19	26.49	21.43

P+O =Potato intercropped with onion, P+C = Potato intercropped with cabbage, P+GP= Potato intercropped with garden peas

TABLE 6. Effect of potato bacterial wilt on average tuber yield (t ha^{-1}) under different intercropping systems

Cropping regime	Nyandarua	Nakuru	Bomet	Bungoma	Mean potato yield
P+O	12.5c*	11.4d	16.6d	11.1b	12.9d
P+C	12.1c	9.7cb	14.9c	10.8b	11.9c
P+GP	10.7b	8.7b	12.9b	10.3b	10.7b
P mono	8.4a	6.1a	9.5a	7.5a	7.9a
LSD	0.845	1.24	1.53	1.13	0.92
CV %	5.98	10.67	8.76	8.77	6.58
F value	33.22	21.52	26.29	14.70	37.17
P value	.00003	.00019	.00009	.00081	.00002

* Means in the same column followed by the same letter (a, b, c) are not significantly different using Least significance difference (LSD) test, $\alpha = 0.05$. P+O =Potato intercropped with onion, P+C = Potato intercropped with cabbage, P+GP = Potato intercropped with garden peas, P mono= Potato mono crop

recorded the lowest potato with the yield of6.1 t ha^{-1} in Nakuru (Table 6).

Corelationships among disease and plant parameters. There was a positive correlation between potato bacterial wilt disease incidence (r = 0.931; $P<0.069$) and severity (r = 0.921; $P<0.079$); each against AUDPC (Table 7). On the other hand, there was a negative correlation between potato tuber yield and disease severity (r = -0.717; P=0.283), and disease incidence (r = -0.697, P = 0. 303) and AUDPC (r = -0.697, P = 0. 303) (Table 7). There was a negative correlation between disease severity and yield (r = -0.717, P = 0. 283); and positive correlation between disease severity and AUDPC (r = 0.856, P = 0.144).

Land Equivalent Ratios. Intercropping potato with onions, cabbages or garden peas was beneficial in increasing food output per unit land area (Table 8). In Nyandarua, LER from intercropping potato with either onions, cabbages or garden peas ranged from 1.35 with garden peas to 1.64 with onions (Table 8); while in Nakuru, LER ranged from 1.42 with garden peas to 1.86 with onions. The LER for potato and onion intercrop (1.86) was the highest which was recorded in Nakuru while the lowest LER for potato and garden pea intercrop (1.35) was the lowest which was recorded in Nyandarua

TABLE 7. Correlation relationship between bacterial wilt disease incidence, severity, tuber yield and area under disease progression curve

Variable	BWI	Severity	Yield	AUDPC
BWI	0.931	-0.697	0.921	
Severity	0.931	-	-0.717	0.856
Yield	-0.697	-0.717	-	-0.697
AUDPC	0.921	0.856	-0.697	-

AUDPC = Area under disease progress curve; BWI = Bacterial wilt incidence

TABLE 8. Land Equivalent Ratios for sole and intercrop arrangements

Cropping regime	PLER O	PLER C	PLER G	PLER P	TLER
Nyandarua					
P+O	0.54	-	-	1.64	2.18
P+C	-	0.63	-	1.51	2.14
P+GP	-	-	0.37	1.35	1.72
Nakuru					
P+O	0.58	-	-	1.86	2.44
P+C	-	0.61	-	1.59	2.20
P+GP	-	-	0.27	1.42	1.69
Bomet					
P+O	0.85	-	-	1.75	2.60
P+C	-	0.67	-	1.57	2.24
P+GP	-	-	0.40	1.36	1.76
Bungoma					
P+O	0.48	-	-	1.48	1.96
P+C	-	0.53	-	1.44	1.97
P+GP	-	-	0.23	1.37	1.60

Pooled data for two seasons; P+O = Potato intercropped with onion, P+C = Potato intercropped with cabbage, P+GP = Potato intercropped with garden peas

DISCUSSION

Disease incidence and severity. The consistently lowest disease incidence recorded in potato-onion intercrop, irrespective of site could be attributed to the ability of onion to improve the efficiency of nutrient utilisation in the intercropping system (Li *et al*., 2018).

Onion in an inter-cropping system has been reported to improve the uptake of phosphorus and improve community structure and function as phosphobacteria in plants' rhizosphere; which has been reported in some studies to reduce bacterial wilt incidence (Wu *et al*., 2016; Hongjie *et al*., 2017; Guji *et al*., 2019). Additionally, low bacterial wilt incidence in the onion intercrop could be attributed to the production of exudates by onion roots which contain saponins, phenols and N-cinnamic amides. These compounds have been reported to inhibit growth of *Verticillium wilt* by inhibiting its amylase, pectinase, and cellulose activities in an intercropping regime (Fu *et al*., 2015).

Low bacterial wilt incidence and severity in potato-cabbage intercrop may also be attributed to the presence of Isothiocyanates compounds in cabbages, which have been reported to suppress bacterial wilt (Iraboneye *et al*., 2020; Poveda *et al*., 2020; Oloyede *et al*., 2021). Isothiocyanates are stress response chemicals formed from glucosinolates in plants in the *Cruciferae* family; and more broadly the brassica genus (Phalliyaguru *et al*., 2018). Once hydrolysed, they generate a range of bioactive compounds. These provide an important defense mechanism against pathogen attacks (Phalliyaguru *et al*., 2018; Liu *et al*., 2021).

These results agree with the findings of Florence *et al*. (2018) while conducting a survey on potato bacterial wilt in Rwanda, where low bacterial wilt disease incidence was associated with inter-cropping, crop rotation, and avoidance of sharing of used farm tools. The lowest bacterial wilt incidence was also recorded on potato-onion inter-crop.

Similarly, there was low bacterial wilt incidence and severity in potato and garden peas inter-crops (Tables 2 and 3). This could be attributed to the ability of garden peas as a legume to improve several aspects of soil fertility, including nitrogen, phosphorus and potassium availability (Yuvaraj *et al*., 2020). In addition to the legume being a good bio-fixer of N, application of nitrogen and phosphorus has been reported to reduce bacterial wilt in potatoes by 29- 50% in Uganda (Yuliar and Koki *et al*., 2015). Therefore, these three potato intercrop regimes possess great potential for integration into bacterial wilt integrated management systems in Kenya.

Area under disease progress curve (AUDPC). The highest level AUDPC (1821.4) recorded in potato monocrops, against lower AUDPC values associated with the intercrop, may be due to bacterial wilt disease dilution effect; where plant species in an intercrop can lower the total host density of a particular crop in the field (Keesing and Ostfeld, 2021). As a result, the disease may have fewer host plants to infect, which would lessen its overall severity and incidence; and reduce disease proliferation.

These results are similar to what was reported by Victoria *et al*. (2022); where it was noted that intercropping reduced disease progression in the field. Low AUDPC in potato intercrops may also be because of changes to microenvironments in which intercrops have been presumed to affect the humidity, temperature, and airflow of field microenvironments; thereby reducing the impact on the onset and development of diseases (Shemeles *et al.,* 2022). This is an area that deserves more elaborate investigations with regards to the potato bacterial wilt, under Kenyan conditions. It has also been reported that intercropping can reduce AUDPC due to biological effect of some intercrop combinations that enhance the presence of beneficial organisms that help in the control of disease causing organism (Frederic *et al.,* 2020). This is also a matter for further investigation under potato growing regions of Kenya.

Corelations among disease and plant parameters. The strong and positive correlation of potato bacterial wilt disease incidence and disease severity (r =0.931, (P<0.05) (Table 7) is an indication that the increase in number of incidence cases, the likelihood increase in severe cases. This further highlights the importance of implementing appropriate control measures against the disease to reduce yield losses. These results are similar to those reported by Bekele (2016); that a positive correlation exists between bacterial wilt incidence and severity of damage; while negative between potato bacterial wilt incidence and yield in Ethiopia. Technically, this means that knowledge of one of them can lead a researcher to predict the magnitude of the other; although this might vary from location to the other due to differences in micro and macro weather conditions.

The generally negative correlations between bacterial wilt incidence (r = -0.697; P=0.069); and severity (r = -0.717; P=0.283), with potatoes tuber yield, imply that joint bacterial wilt incidence and severity result in marked reductions in potato yield. The low yield recorded in the potato pure stands may be attributed to higher bacterial wilt activity, resulting in greater incidence and severity in both sites. The study demonstrates the potential role of onions, cabbage and garden peas in managing potato bacterial wilt disease under field conditions in Kenya. There is, therefore, a need to integrate these interventions in the bacterial wilt management programmes of the country.

Land Equivalent Ratios. All intercropping arrangements had total LERs greater than 1.00, a good indication of efficient resource utilisation by the intercrop regimes, in addition to suppressing the wilt disease burden on the potato component. The highest LER of 2.18 obtained in the potato- onion intercrop, indicates that an additional land area of 1.18 ha would be required to obtain similar onion and potato tuber yield when planted as sole crops. The highest LER from the potato-onion intercrop could have resulted from the joint reduction in incidence and severity of bacterial wilt disease on potato plants, and more optimum utilisation of land area compared to the pure stands of the components. This phenomenon, however, still requires more elaborate investigations to arrive at the most appropriate field architecture for the different intercrop combinations in the field.

CONCLUSION

Intercropping potato with onions, cabbages or garden peas reduces the incidence and severity of bacterial wilt disease considerably; thus resulting in greater LER and its associated benefits in Kenya. The potato-onion and sometimes potato-cabbage intercrops are top performers in terms of suppressing disease incidence and severity; and increases potato tuber yield. In spite of these positive observations, there is a clear need for ascertaining the optimum field architecture of this promising potato intercrops so as for farmers to optimise the use of potato production resources in the field. It is also imperative to involve a diversity of potato genotypes and different varieties of intercrop components so as to generate a basket of options for farmers to select from.

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