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Evaluation of the Efficacy of Different Levels of Inorganic Salts and Varieties for the Management of Late blight of Potato under Laboratory and Field Conditions

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Abstract

Resistance to late blight disease in potato varieties is broken down due to the emergence of virulent races of Phytophthora infestans. There is no variety grown without fungicide spray. Chemicals pose a serious threat to the environment and human health. Laboratory study was conducted at Adet plant pathology lab in 2018 and field studies were conducted at Adet and Debre Tabor experimental sites in 2018 and 2019. The objective of the study was to determine the effect of inorganic salts and host plant resistance against late blight of potato. Eight inorganic salts were evaluated in the laboratory in detached leaf assay technique and effective inorganic salts were selected and integrated with three potato varieties in factorial arrangement in the field. Results of the laboratory study indicated that inorganic salts posed significant ($P<0.01$) inhibitory effect on infection and lesion growth. Treating leaves with Ridomil fungicide, Potassium phosphite and Potassium phosphate at the rate of 20 g l^{-1} reduced leaf lesion area by 99.4, 95.6 and 95.5%, respectively. The effect of inorganic salt by variety interaction on the area under disease progress curve (AUDPC) was significant ($P<0.01$). The fungicide sprayed plots significantly reduced the AUDPC values on the varieties. But, such reductions were not significant compared to potassium phosphite sprayed plots of Belete and Gudene varieties over locations. The relative yield loss of the untreated (control) plots of the susceptible variety (Jalene) were 43.21 and 59.74%, whereas K_2HPO_3 treated plots were 18.63 and 15.64% in 2018 and 2019 respectively. Therefore, even treating susceptible varieties with inorganic salts could result in minimizing the damage of late blight disease on potatoes. In conclusion, integration of potassium phosphite with resistant (Belete) and moderately resistant (Gudene) varieties is identified as the best alternative option to manage late blight of potato.

Keywords: Detached leaf assay; Level of resistance; Potassium phosphite; Potassium phosphate

Introduction

In Ethiopia, potato is one of the important crops for food and nutrition security where food security is a key priority. However, the production and productivity of potato are constrained by late blight disease caused by *Phytophthora infestans* (Kyamanywa *et al*., 2011). The disease occurs throughout the major potato production areas and it is difficult to produce in the main rainy season without chemical protection measures (Habtamu *et al*., 2012). It causes yield losses of up to 100% in epidemic conditions (Bekele and Medhin, 2000). To manage the disease effectively, farmers have increasingly adopted fungicide management as the main control option.

Management strategies for the effectiveness of this disease control include among others the use of host resistance, chemicals, biocontrol, forecasting, sanitation and even disease escape mechanisms (Wastie, 1991; Singh and Sharma, 2013). The use of fungicides in controlling late blight was found to boost potato yield in Ethiopia (Mesfin and Gebremedhin, 2007). Ridomil fungicide has failed in giving perfect control of the late blight disease (Mesfin and Gebremedhin , 2007). It is observed that host plant resistance broke down with a subsequent increase in the level of susceptibility to late blight diseases due to the emergence of virulent races (Gebremedhin, 2013). Currently there is no single variety grown without fungicide spray in favorable conditions for the late blight disease development in Ethiopia. Moreover, the development of metalaxyl resistant races of *P. infestans* had made the systemic fungicide inefficient in Ethiopia (Schiessendoppler *et al*., 2003). The indiscriminate use of these chemicals poses a serious threat to the environment and also to human health hence, potato growers look for management technologies which can substitute chemical control. Inorganic salt control has attracted much attention because of its eco-friendly effect on the environment and the crop (Harmendez *et al*., 2005). Recent years have witnessed the increasing popularity of inorganic salts as an alternative to fungicides (Smilanick *et al.*, 2006; Zaker, 2016).

Inorganic salts like potassium phosphites are probably more capable due to indirect and direct effects. Indirect effects by inducing defense reactions in the plant and also have a direct inhibiting effect on the growth and sporulation of the oomycetes (Fenn and Coffey, 1989; Grant *et al*., 1990; Smillie *et al*., 1989). In some developing countries (Kenya, Peru, Ecuador), phosphite salts have been promoted and are used against the disease since they are found comparable in controlling the disease and pose lower risks for human health and the environment compared to conventional fungicides (Kromann *et al*., 2012). In many tropical countries, phosphites provide control efficacy comparable to conventional contact fungicides, such as mancozeb and chlorothalonil. Furthermore, the control appeared to be relatively stable across locations (Kromann *et al*., 2012).

Since the disease spreads very fast in the fields when the environmental conditions are conducive, in such cases management of late blight through single management option may not be effective, particularly inorganic salt management by its own may not be efficient enough for the management of such a devastating disease but may play a role if combined with other methods such as resistance varieties and reduced fungicide treatments (Zaker, 2016). Hence, identification and logical integration of strategies that would contribute towards suppression of the pathogen and/or supporting the host resistance is important. This approach is helpful to disease management to avoid over reliance on fungicides, which increases the risk of selecting fungicide resistant strains in the pathosystem. Therefore, the objective of this study was to determine the effect of inorganic salts and host resistance on late blight of potato in Ethiopia.

Materials and Methods

Description of the study area

Inorganic salt evaluation was carried out at the Plant Pathology Laboratory of Adet Agricultural Research Center in January 2018. Integrated field experiments were conducted during the 2018 and 2019 main cropping seasons at two locations at Debre Tabor and Adet, northwestern Ethiopia, from June to October (Table 1).

Table 1. Experimental site description for integrated management of potato late blight in northwestern Ethiopia.

Variable	Variable	Location	
		Debre-Tabor	Adet
Geographical position	Latitude	11.89^{o}N	11.16^{o}N
	Longitude	38.04^{o}E	37.29^{o}E
Altitude (m a.s.l.)		2650	2240
Annual total Rainfall (mm)		1500	1211
Mean Temperature (^{o}C)	Minimum	11.8	11.57
	Maximum	23	26.89
Soil type		luvisol	Nitosol
Agro-climatic condition			

Laboratory evaluation of inorganic salts

Phytophthora infestans inoculum preparation

The isolate of *P. infestans* was obtained from an infected potato plant in the field and isolated using the International Potato Center (CIP) laboratory protocol (CIP, 2007). A sporangial suspension prepared from sporulated tuber slices adjusted to a concentration of 2×10^4 sporangia ml^{-1}, by using haemocytometer, and conditioned for 2 hours at 4°C to stimulate the release of zoospores from sporangia.

Inorganic salt preparation

Eight inorganic salts, i.e. potassium phosphite (K_2HPO_3), potassium phosphate (K_2HPO_4), ammonium bicarbonate (NH_4HCO_3), sodium bicarbonate ($NaHCO_3$), potassium carbonate (K_2CO_3), potassium bicarbonate ($KHCO_3$), sodium chloride ($NaCl$), and potassium chloride (KCl) were obtained from Adet soil laboratory and Haramaya University but ammonium bicarbonate was purchased from local market in Addis Abeba. For each of the tested salts four concentrations (5, 10, 15 and 20 g L^{-1}) (El-Mougy and Abdel-Kader, 2009) were prepared by dissolving in sterilized distilled water. Ridomil Gold at the rate of 8 g L^{-1} and distilled water treated leaflets were included as a control.

Preparation of potato plants

Healthy *in vitro* plantlets of susceptible Jalene potato variety were obtained from Amhara Regional Agricultural Research Institute tissue culture laboratory (ARARI-TCL), Bahir Dar. The *in vitro* plantlets were cultured in the screen house at Adet Agricultural Research Center in Pots filled with sterile soil covered with plastic. Fresh leaves from 6 - 8 weeks old plants were collected and used for detached leaf assay.

Detached leaf assay

The collected detached leaves were sprayed with the salt solution prepared in sterile distilled water at predetermined concentration. Free moisture from treated leaves were removed by drying in shade and placed upside down on the lids of inverted Petri dishes with the dishes lined with 1.5% water agar in the base. Sporangia suspension (2×10^4 sporangia ml^{-1}) was dropped at the center of each leaflet and the plates were sealed with parafilm and incubated at 18 °C under dark for 48 hours then with a photoperiod of 16 hours light and 8 hours dark cycle for 6 days. The experimental design was completely randomized design (CRD) and replicated three times. The experiment was repeated once.

Data collection

Length and width of lesions were measured after 7 days of incubation and the lesion area was calculated as- Area = $\pi ab/4$ (Singh and Bhattacharya, 1995). Where, a and b were the length and width of the lesion, respectively. The effect of the treatments on lesion area was calculated in percent.

Field Experiment (Integration of effective inorganic salts with host resistance)

Experimental design and treatments

Effective inorganic salts identified in the laboratory experiment such as potassium phosphate (K_2HPO_4), potassium phosphite (K_2HPO_3), fungicide (Ridomil) and untreated control were combined with Belete (relatively resistant), Gudene (moderately resistant) and Jalene (relatively susceptible) potato varieties. The treatments were laid out in a randomized complete block design (RCBD) in a factorial arrangement in three replications. Each potato variety treatment was assigned to one plot in each replication in six rows with 10 plants. The gross plot size was 13.5 m^2 (4.5 m x 3 m) with 0.75 m and 0.3 m spacing between rows and plants, respectively. A spacing of 1.5 m and 1 m was maintained between plots and blocks, respectively. The central rows were used to estimate tuber yield and late blight severity. The recommended fertilizers at the rate of 81 kg N ha^{-1} and 69 kg P_2O_5 ha^{-1} at Adet and 108 kg N ha^{-1} and 69 kg P_2O_5 ha^{-1} at Debre Tabor were applied. Split application was adopted for urea (½ at planting and ½ 30 days after emergence) but phosphorus was applied at planting. Potassium phosphite and phosphate were applied at the rate of 20 g L^{-1} whereas the fungicide was applied at a rate of 2.5 kg ha^{-1} starting from the onset of the disease at 40 and 36 days after planting in 2018 and 2019 at 10 days interval. With this four times spray has been made. During the time of spray, plastic sheets were used to avoid drifts.

Disease assessment

Disease Severity: Disease severity was recorded from 10 pre-tagged plants of the middle 4 rows at seven days interval starting from disease onset (at 40 days from planting) until senescence (8 times) visually and was estimated using the following formula.

Disease severity was assessed by using 1- 9 point scale as suggested by Henfling (1987).

$Disease\ severity\ (S) = \frac{Area\ of\ diseased\ tissue}{Total\ tissue\ area}\ x100$The severity grades were converted into percent severity index (PSI) for analyses using the formula suggested by Wheeler (1969):

$$PSI = \frac{Snr}{Npr\ x\ Mss} x100$$

Where Snr = the sum of numerical ratings, Npr = number of plants rated, Mss = the maximum score of the scale.

Area under disease progress curve (AUDPC): Area under the disease progress curve (AUDPC) was calculated for each plot using the following formula (Shaner and Finney, 1977):

$$AUDPC = \sum_{i=1}^{n-1} \quad 0.5(xi + xi + 1)(ti + 1 - ti)$$

Where xi is the disease severity expressed in PSI at i^{th} observation, t_i, is time (days after planting) at the i^{th} observation, t' is the epidemic duration for each treatment and n is total number of disease assessments made.

Disease progress rate: The rate of foliar disease development was quantified by repeated assessments of the percentage of leaf and stem area affected by the disease starting 40 and 36 days after planting in 2018 and 2019, respectively. The disease infection rate (r) was calculated based on the linearized logistic model (Van der Plank, 1963; Campbell and Madden, 1990) and the calculated value was analyzed:

$$r = (ln\frac{Y}{1-Y}) - (ln\frac{Yo}{1-Yo})/t$$

Where r is disease progress rate, Yo is initial disease severity, Y is the final disease severity and **t** is the duration of the epidemic ln = Natural logarithm.

Yield and yield components

At harvest marketable, unmarketable and total tuber yields were measured for each plot from the four middle rows. Total tuber yield was calculated by converting the total weight of all the tubers harvested in each plot into t ha^{-1}. Yield data was directly analyzed and relative yield loss was calculated using the formula of Robert and James (1991).

$$\%L = \frac{YP - YT}{YP} * 100$$

Where L = relative percent yield loss, YP = yield from the maximum protected plot and YT = yield from plots of other treatments (i.e. with different levels of diseases).

Yield increase over the change of yield increase to untreated plots was calculated with the formula:

$$YIU = \frac{YT - YU}{YT} * 100$$

Where YIU = relative yield increase over untreated, YT = treated yield and YU = untreated yield.

Data analysis

The error variances homogeneity test using F-ratio (Gomez and Gomez, 1984) was tested prior to the combined ANOVA is performed. The two seasons were considered as different for most of the parameters because of heterogeneity of error variances as tested using Bartlett’s test (Gomez and Gomez, 1984) and the F-test was significant. Thus, the season data were not combined for analysis; whereas the locations were not considered as different environments; because of homogeneity of variances as tested and data were combined for analysis. Data were subjected to analysis of variance (ANOVA) using general linear model (GLM) procedure of SAS software version 9.2 software (SAS, 2009). Whenever ANOVA detected significant difference between treatment means, the Duncan Multiple Range Test (DMRT) was used for mean comparison. For correlation analysis, the PROC CORR option of the ANOVA procedure was used. A significant level of $\alpha = 0.05$ was used in all analyses.

Results and Discussion

Effect of inorganic salts on lesion area

The lesion area had highly significant differences ($P < 0.01$) among inorganic salts. The lowest lesion area (2.3 mm^2) from the combined analysis of the two runs was obtained from Ridomil® gold fungicide treated leaves but this lesion area was not statistically significant with potassium phosphite and potassium phosphate treated leaves at the rate of 20g L^{-1}which had 8.9 mm^2 and 9 mm^2, respectively. Leaves treated with distilled water had the highest (199.7 mm^2) lesion area and were highly ($P < 0.01$) significantly different (Table 2). All inorganic salt treatments had statistically significant effects against late blight compared to the distilled water treated /control/ treatment. Potassium phosphite and potassium phosphate at the rate of 15g L^{-1} had also a statistically significant effect against *P.infestans* as compared to the other inorganic salt treatments on the lesion area. Other inorganic salt treatments such as sodium bicarbonate, potassium carbonate, sodium chloride, potassium chloride, and ammonium bicarbonate inhibited infection and lesion area to a lesser extent as compared to potassium phosphite, potassium phosphate and potassium bicarbonate even though they showed significant differences when compared with the untreated /distilled water treatments. Our finding is in agreement with Machinandiarena *et al. (*2012) who reported that potassium phosphite application restricted lesion development and pathogen biomass in potato leaves. It is also consistent with Lobato *et al.* (2008) who indicated that potassium phosphite was able to protect potato leaves against *P.infestans*.

Effect of inorganic salts, host resistance and Metalaxyl on Late blight of Potato epidemic

Disease severity

The percent severity index (PSI) analysis was performed from the disease assessment data. The PSI showed a highly significant difference ($P < 0.01$) among treatments across locations in 2018 and 2019 at the final disease assessment (at 89 in 2018 and 85 in 2019 days after planting). During the final period of disease assessment, the highest PSI (82.59%) was recorded on unsprayed plots of Jalene and lower PSI (23.3, 23.31 and 24.07%) were recorded from Belete, Gudene and Jalene varieties treated with fungicide (Ridomil), in that order. The lower PSI value of (30.64%) recorded from K_2HPO_3 treated plots of Belete variety and followed by (33.13 and 31.72%) K_2HPO_3 treated plots of Gudene and Jalene, correspondingly, but the differences were not statistically significant from K_2HPO_3 treated plots of resistant (Belete) variety across locations in 2018. Similarly, in 2019 the highest PSI (100%) was recorded from unsprayed plots of Jalene variety and lower PSI value of 29.07, 32.59 and 31.48% were recorded from fungicide treated plots of Belete, Gudene and Jalene varieties, respectively. The differences were not statistically significant from potassium phosphite treated plots of Belete and Gudene varieties. All treatments had a statistically significant effect against late blight as compared to the untreated control (Table 3 and 4; Fig 1 and 2).

Table 2. Effect of inorganic salts on potato late blight lesion area and lesion area reduction in percent on the detached leaf.

Salt	Rate (g L^{-1})	Area (mm^2)	Lesion area reduction (%)
K_2HPO_3	5	84.0^{j}	57.3^{e}
	10	66.1^{k}	68.9^{d}
	15	35.7^{m}	80.2^{b}
	20	8.9^{n}	95.6^{a}
K_2HPO_4	5	82.7^{j}	58.5^{e}
	10	58.9^{kl}	70.5^{cd}
	15	44.3^{lm}	77.8^{bc}
	20	9.0^{n}	95.5^{a}
$KHCO_3$	5	123.8^{h}	37.9^{g}
	10	106.4^{i}	46.7^{f}
	15	84.5^{j}	57.6^{e}
	20	62.2^{k}	68.8^{d}
$NaHCO_3$	5	168.3^{b-d}	15.5^{k-m}
	10	164.6^{b-e}	17.4^{j-m}
	15	152.6^{c-g}	23.4^{h-l}
	20	143.7^{g}	27.8^{h}
K_2CO_3	5	173.2^{b}	13.2^{m}
	10	164.2^{b-f}	17.6^{i-m}
	15	159.8^{b-g}	19.9^{h-m}
	20	152.4^{c-g}	23.5^{h-l}
NH_4HCO_3	5	166.4^{b-d}	16.4^{k-m}
	10	158.3^{b-g}	20.5^{h-m}
	15	145.7^{e-g}	26.7^{h-j}
	20	145.5^{g}	26.9^{h-j}
NaCl	5	173.6^{bc}	14.3^{lm}
	10	164.2^{b-f}	17.7^{j-m}
	15	149.6^{dg}	25.2^{h-k}
	20	145.1^{g}	27.3^{hi}
KCl	5	173.4^{b}	13.2^{m}
	10	158.7^{b-g}	20.6^{h-m}
	15	150.0^{d-g}	25.0^{h-k}
	20	145.6^{e-g}	27.2^{hi}
Ridomil® gold	10	2.3^{n}	99.4^{a}
Water treated control	dH_2O	199.7^{a}	---
Mean		117	39.2
$P < 0.05$		**	**
CV (%)		11.5	18.1

Data were the means of repeated laboratory experiments.

*Means with different letter(s) in the same column are significantly different ($P < 0.05$), CV = coefficient of variation, **= highly significant*

Area under disease progress curve

The area under the disease progress curve (AUDPC) showed a highly significant ($P < 0.01$) effect between treatments (Table 3 and 4). The highest AUDPC (2172.5) was calculated or obtained on the unsprayed plots of Jalene variety while the lower AUDPC (672.6, 764.8 and 894.3) were obtained on fungicide treated plots of Belete, Gudene and Jalene varieties, respectively and AUDPC (928.9 and 1001.3) on K_2HPO_3 treated plots of Belete and Gudene varieties in that order in 2018 across locations analysis. In 2019 the highest AUDPC (2833.62) was found on unsprayed plots of Jalene and lower AUDPC (947.37, 1013.58 and 1046.26) on fungicide treated plots of Belete, Gudene and Jalene varieties and AUDPC (1086.31 and 1259.31) on K_2HPO_3 treated plots of Belete and Gudene varieties across locations. Therefore, the differences between fungicide and potassium phosphite treated plots were not significantly different. The best treatments in reducing the AUDPC in the potato varieties were obtained when the fungicide was applied at the recommended rate; similarly, when potassium phosphite was applied at 20g L^{-1}. Therefore, the differences between the treatments which received the fungicide and potassium phosphite were statistically insignificant i.e the average values of AUDPC were comparable with fungicide (Ridomil) treated plots.

Disease progress rate

The disease progress rates (DPRs) among treatments were highly significant ($P < 0.01$) affected across locations in both years. The highest DPRs (0.0682 units per day) was obtained from unsprayed plots of Jalene and lower DPRs (0.018, 0.0184 and 0.0132 units per day) were obtained from fungicide treated plots of Belete, Gudene and Jalene varieties, correspondingly. K_2HPO_3 treated plots of Belete variety across locations had 0.0191 units per day in 2018. In 2019, the highest (0.0914) was calculated on unsprayed plots of Jalene variety and lower DPRs (0.0266, 0.0286 and 0.0292 units per day) on fungicide treated plots of Belete, Gudene and Jalene varieties, in that order and (0.0322 and 0.033 units per day) on K_2HPO_3 treated plots of Belete and Gudene varieties, respectively across locations (Tables 3 and 4). The differences were not significantly different between fungicide and K_2HPO_3 sprayed plots. When comparing the two years, the higher mean disease progress rate was obtained in 2019 than 2018. From this result disease progressive rate was faster in unsprayed susceptible potato varieties than K_2HPO_3, K_2HPO_4 and fungicide (Ridomil) sprayed plots.

Tuber Yield

The analysis of variance showed a highly significant ($P< 0.05$) difference among treatments for tuber yield. All the treatments gave significantly higher marketable tuber yields compared to the untreated control treatment (Table 3 and 4). Higher marketable tuber yields (41.31 and 34.44 t ha-^{1}) were obtained from Belete sprayed with Ridomil and the lower (20.73 and 11.92 t ha-^{1}) were obtained from unsprayed plots of Jalene across locations in 2018 and 2019, respectively. But, the marketable tuber yields were not significantly different from the K_2HPO_3 treated plots. Generally, the average marketable and total tuber yields were higher from the Ridomil treated plots of Belete, Gudene and Jalene varieties. However, the marketable and total tuber yields were not significantly different from the K_2HPO_3 treated plots of Belete variety. The highest unmarketable tuber yield was recorded from unsprayed (control) plots of Jalene variety in both years across locations. The untreated controls in all varieties caused higher late blight severity and lower yield compared to the treated plots. All other treatments showed significantly better than untreated controls. Analysis of variance revealed that K_2HPO_3 had a relatively better effect indicated by lower AUDPC, DPR and PSI_f values. Additionally, marketable and total tuber yields were close to those obtained with the recommended rate of Ridomil treatments. It appeared that K_2HPO_3 performed almost comparable to Ridomil fungicide application.

Table 3: Interaction effects of inorganic salts and fungicide application and potato varieties on late blight of potato PSI_f, AUDPC, DPR, and MTY, UMTY and TTY across two locations in 2018 main season under natural infection.

Variety	Salt	AUDPC	DPR	PSI_f	MTY	UMTY	TTY
Belete	K_2HPO_4	1089.1cd	0.0281d	39.17cde	36.42ab	1.03cd	37.45abc
	K_2HPO_3	928.9def	0.0191ef	30.64fgh	36.84ab	0.82cde	37.66ab
	Ridomil	672.6f	0.018ef	23.30h	41.32a	0.27ef	41.59a
	Control	1273.9c	0.0375c	41cd	29.85bc	1.22bc	31.07bcd
Gudene	K_2HPO_4	1326.1c	0.0278d	40.99cd	26.83cd	0.65def	27.47cd
	K_2HPO_3	1001.3de	0.0287d	33.13def	30.3bc	0.56def	30.86bcd
	Ridomil	764.8ef	0.0184ef	23.31h	32.87bc	0.15f	33.03bc
	Control	1752.8b	0.0519b	64.16b	21.62d	1.67b	23.86d
Jalene	K_2HPO_4	1326.3c	0.0324cd	42.64c	26.68cd	0.77cde	27.44cd
	K_2HPO_3	1124cd	0.0256de	31.72efg	29.7bc	0.76cde	30.47bcd
	Ridomil	894.3def	0.0132f	24.07gh	36.5ab	0.21f	36.7ab
	Control	2172.5a	0.0682a	82.59a	20.73d	2.34a	23.07d
Mean		1193.88	0.0307	39.73	30.81	0.87	31.54
CV (%)		18.18	21.32	16.09	20.47	48.85	19.71
$P < 0.05$		**	**	**	*	**	*

Mean with the same letters in the column are not significantly different, AUDPC = area disease progress curve, DPR = disease progress rate, PSI_f = percent severity index at the final assessment (89 days after planting), MTY $t\ ha^{-1}$ = marketable tuber yield tons per hectare; UMTY $t\ ha^{-1}$ = unmarketable tuber yield tons per hectare and TTY $t\ ha^{-1}$ = total tuber yield tons per hectare CV = coefficient of variation, *= significant difference.**= highly significant difference.

Table 4. Interaction effects of inorganic salts and fungicide application and potato varieties on AUDPC, PSI_f, DPR, MTY, UMTY and TTY of late blight of potato across locations in 2019 main season under natural infection..

Variety	Salt	AUDPC	DPR	PSI_f	MTY	UMTY	TTY
Belete	K_2HPO_4	1247.22de	0.0376cd	47.22d	26.39bcd	0.64c	27.02bc
	K_2HPO_3	1086.31ef	0.0322cd	38.89e	33.27ab	0.58c	33.86ab
	Ridomil	947.37f	0.0266d	29.07ef	34.44a	0.2c	34.65a
	Control	1326.81d	0.0440c	50.74d	22.39cde	1.35b	23.75cd
Gudene	K_2HPO_4	1259.31de	0.0405cd	47.59d	21.96cde	0.48c	22.45cd
	K_2HPO_3	1082.52ef	0.0330cd	39.07e	26.37bcd	0.47c	26.83bc
	Ridomil	1013.58f	0.0286d	32.59ef	28.18a-d	0.2c	28.38abc
	Control	1683.52c	0.0595b	67.78c	21.36de	1.26b	22.62cd
Jalene	K_2HPO_4	2109.91b	0.0580b	78.52b	18.2ef	0.52c	18.53ed
	K_2HPO_3	1938.93b	0.0463bc	72.41bc	24.98cde	0.52c	25.49cd
	Ridomil	1046.26f	0.0292d	31.48ef	29.61abc	0.14c	29.75abc
	Control	2833.62a	0.0914a	100a	11.92f	2.15a	14.07e
Mean		1464.61	0.0439	52.9467	24.92	0.71	25.62
CV (%)		10.67	26.64	12.49	23.66	67.96	22.57
$P < 0.05$		**	**	**	*	**	*

Mean with the same letters in the column are not significantly different, AUDPC = area disease progress curve, DPR = disease progress rate, PSI_f = percent severity index at 85 days after planting , MTY t ha^{-1} = marketable tuber yield tons per hectare; UMTY t ha^{-1} = unmarketable tuber yield tons per hectare and TTY t ha^{-1} = total tuber yield tons per hectare CV = coefficient of variation, *= significant difference, ** = highly significant difference.

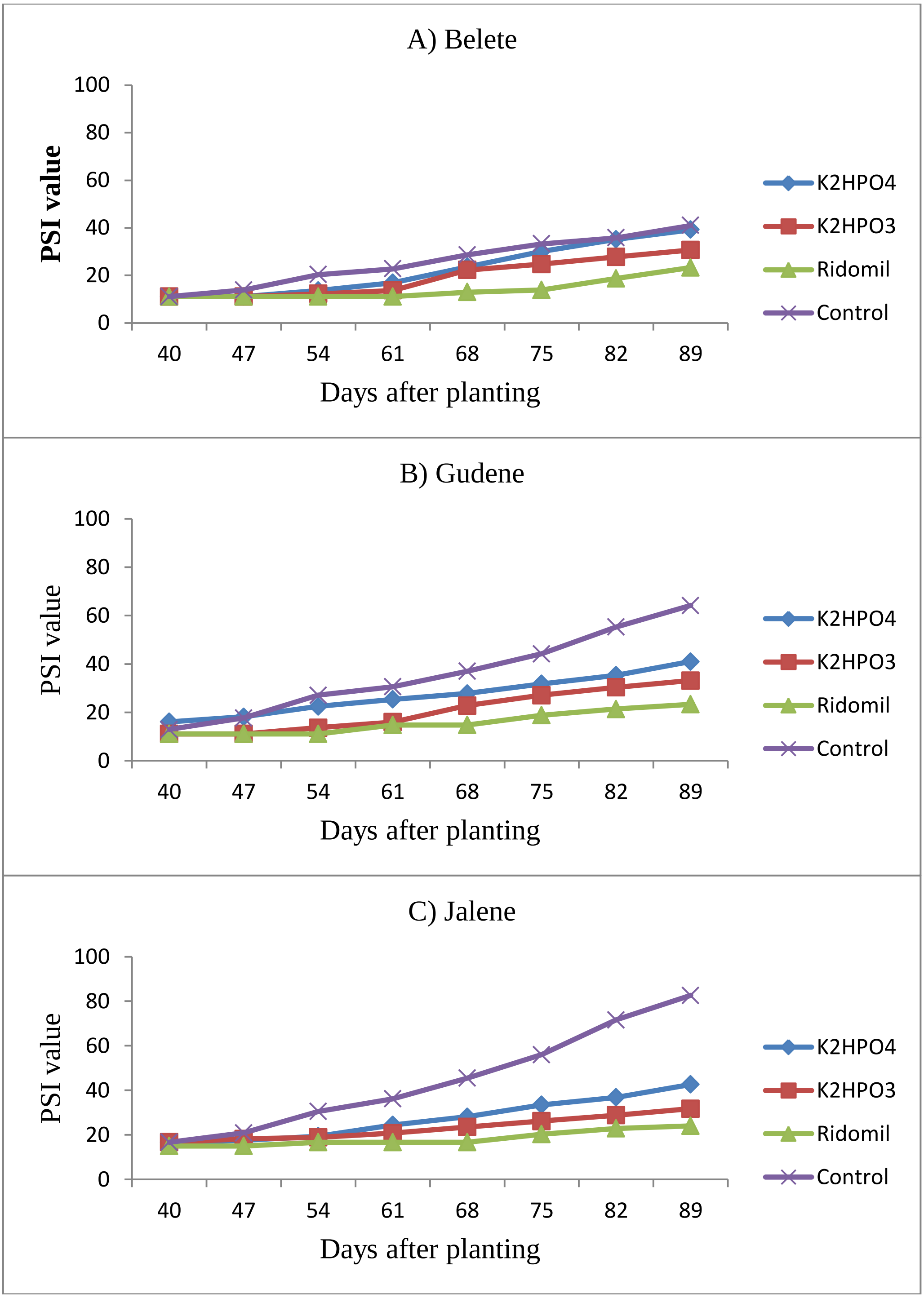

Figure 1: Late blight of potato progress curves as affected by inorganic salt spray on three potato varieties across locations in 2018 main cropping season. Where, K_2HPO_4 = potassium phosphate, K_2HPO_3 = potassium phosphite, Ridomil = fungicide, Control = water spray and PSI = percent severity index

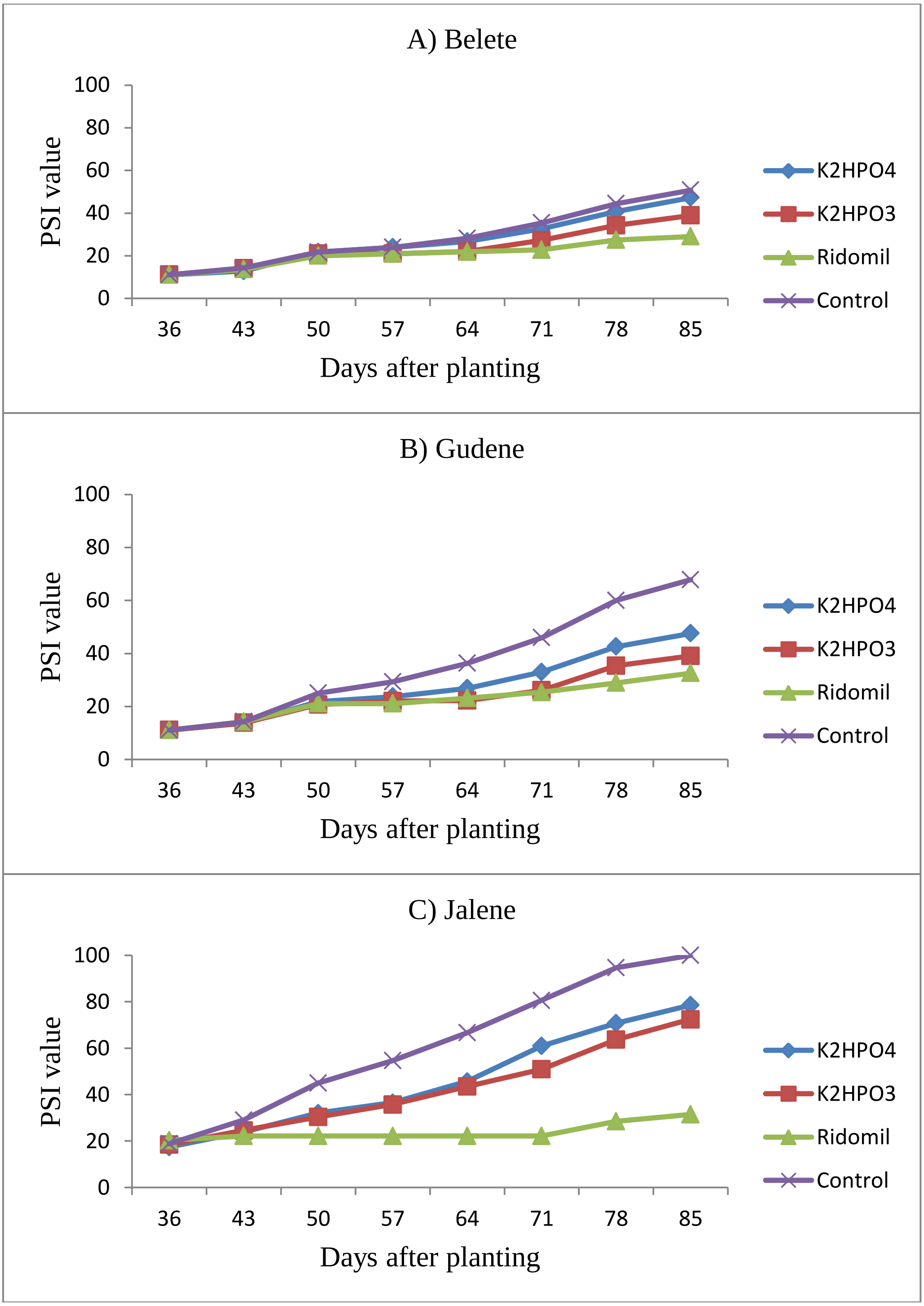

Figure 2: Late blight of potato progress curves as affected by inorganic salt spray on three potato varieties across locations in 2019 main season. Where, K_2HPO_4 = potassium phosphate, K_2HPO_3 = potassium phosphite, Ridomil = fungicide, Control = water spray and PSI = percent severity index.

Relative Tuber Yield Loss

The relative potato tuber yield losses were different for all treatment in both fields (Table 5). The highest marketable tuber yield loss of 43.21% and 59.74% were obtained from unsprayed plots of Jalene variety compared to Ridomil treated plots across locations in 2018 while it was 59.74% on the same variety in 2019. However, treating the Jalane variety with K_2HPO_3 reduced the relative tuber yield loss from 43.21 to 18.63% in 2018 and from 59.74 to 15.64 % in 2019. Yield losses of nearly 43-60% were incurred from unsprayed (control) plots indicating how much late blight disease is damaging to potatoes during favorable conditions when effective management practices are not applied. The 2019 cropping season was more conducive for late blight epidemics to cause higher tuber yield losses in potato production.

Table 5. Effect of potato varieties and inorganic salts on relative yield losses and increases of yield over the controls due to late blight of potato across location under natural infection

Variety	Inorganic Salt	2018			2019		
		MTY (t ha^{-1})	RYL (%)	CYI (%)	MTY (t ha^{-1})	RYL (%)	CYI (%)
Belete	K_2HPO_4	36.42	11.86	18.04	26.39	23.37	15.16
	K_2HPO_3	36.84	10.84	18.97	33.27	3.40	32.70
	Ridomil	41.32	0.00	27.76	34.44	0.00	34.99
	Control	29.85	27.76	0.00	22.39	34.99	0.00
Gudene	K_2HPO_4	26.83	18.38	19.42	21.96	22.07	2.73
	K_2HPO_3	30.3	7.82	28.65	26.37	6.42	19.00
	Ridomil	32.87	0.00	34.23	28.18	0.00	24.20
	Control	21.62	34.23	0.00	21.36	24.20	0.00
Jalene	K_2HPO_4	26.68	26.90	22.30	18.2	38.53	34.51
	K_2HPO_3	29.7	18.63	30.20	24.98	15.64	52.28
	Ridomil	36.5	0.00	43.21	29.61	0.00	59.74
	Control	20.73	43.21	0.00	11.92	59.74	0.00

MTY t ha^{-1} = marketable tuber yield in tons per hectare, RYL= relative yield loss, CYI = change in yield increase over the control.

Correlation of disease parameters and yield

The marketable tuber yield (MTY) and total tuber yield (TTY) of three potato varieties were highly significantly ($P < 0.01$) and negatively correlated with final percent severity index (PSI_f), area under disease progress curve (AUDPC), disease progress rate (DPR) but positively correlated with unmarketable tuber yield (UMTY) across location in 2018 and 2019 (Table 6). This result indicates that the observed values of the disease parameters had a considerable adverse effect on potato tuber yield.

Table 6. Correlation coefficient (r) of late blight of potato disease parameters with yield in potato varieties and inorganic salts application across locations in 2018 (above diagonal) and 2019 (below diagonal).

	PSI_f	AUDPC	DPR	MTY $t\ ha^{-1}$	UMTY $t\ ha^{-1}$	TTY $t\ ha^{-1}$
PSI_f	1	0.9515**	0.9004**	-0.5608**	0.7558**	-0.5166**
AUDPC	0.9495**	1	0.7944**	-0.5182**	0.6858**	-0.4784**
DPR	0.8699**	0.8503**	1	-0.5706**	0.7293**	-0.5291**
MTY $t\ ha^{-1}$	-0.6966**	-0.6208**	-0.6864**	1	-0.5170**	0.9969**
UMTY $t\ ha^{-1}$	0.7643**	0.5910**	0.6790**	-0.5581**	1	-0.4484**
TTY $t\ ha^{-1}$	-0.6179**	-0.5961**	-0.6567**	0.9970**	-0.4921**	1

*** =significant at P<0.01and P<0.05, respectively. PSI_f = Percent severity index at final; AUDPC = area under the disease progress curve; DPR = Disease progress rate; MTY t ha^{-1} = marketable tuber yield in tons per hectare; UMTY t ha^{-1} = unmarketable tuber yield in tons per hectare and TTY t ha^{-1} = total tuber yield in tons per hectare.*

From this study, all the tested inorganic salt and varietal integrations reduced the final percent severity index, the AUDPC and DPR and led to increased tuber yields of the potato varieties. The integration of potassium phosphite with resistant and moderately resistant varieties provided almost a comparable protection against late blight as the conventional full dosage fungicide. In both years, the results showed that potassium phosphite integration with varieties controlled late blight on potato foliage. In this study, based on two years and field studies it is proved that the potassium phosphite has a comparable effect against foliar late blight in potato in northwestern Ethiopia. In potato varieties treated with potassium phosphite, they performed almost as equal as modern fungicide Ridomil. The results also indicated that with relatively resistant potato varieties, the potassium phosphite could be an alternative to significantly reduce disease severity and increase tuber yield. According to Liljeroth *et al.* (2016) in the extremely susceptible varieties, the late blight developed severe even in treatments with recommended doses of fungicides and treatment with phosphite tended to be less effective.

According to Kromann *et al.* (2012) report, potassium phosphite is frequently used against late blight of potato in tropical agriculture and on average, potassium phosphite provided efficacy comparable to that of the conventional fungicides of mancozeb and chlorothalonil at recommended doses. Cooke and Little (2002) reported the good effect of phosphite against late blight but no comparisons were made with traditional fungicides and it is, therefore, not possible to conclude if the efficacy of phosphite was as good as fungicides. Whereas, Mayton *et al.* (2008) reported that phosphite controlled late blight as well as chlorothalonil and tuber blight even better than the fungicide. Wang-Pruski *et al.* (2010) reported that phosphite provided protection against late blight under field conditions but the effect was not as good as with chlorothalonil. However, the best effect was obtained with a combination of phosphite and chlorothalonil. From this study, the potassium phosphite treatment in combination with resistant variety was investigated as almost equally effective as Ridomil for the management of late blight of potato.

In resistant variety like Belete, the effect of potassium phosphite was as good as the effect of modern fungicides as the Ridomil treatment. The study by Liljeroth *et al.* (2016) even in the more resistant starch potato cultivars, potassium phosphite alone may provide sufficient protection. In the susceptible variety like Jalene, the efficacy of phosphite was less than the efficacy of the fungicides /Ridomil/. According to Kromann *et al.* (2012), the efficacy of potassium phosphite in several tropical countries did not correlate to the level of resistance in the cultivars used. However, Liljeroth *et al.* (2016) found that in the more resistant starch potato cultivars the effect of treatment with phosphite was better than in susceptible cultivars. Mohammadi *et al.* (2019) reported that potassium phosphite has been able to activate a general defense response in the potato plants and the response was relatively high in the moderately resistant cultivar and lower in the more susceptible cultivar. The study by Mayton *et al. (*2008) showed that *P. infestans* infection on leaves was well controlled by potassium phosphite as effective as a conventional fungicide against tuber late blight. The report by Lobato *et al.* (2011) also showed that the use of potassium phosphite on the leaves resulted in a series of postharvest defense reactions at field conditions.

The mode of action of phosphite is believed to be induced resistance, involving activation of defense responses and a direct inhibiting effect on the growth and sporulation of the Oomycetes (Grant *et al*., 1990). Potassium phosphite is taken up by plants, has a high degree of phloem mobility and is translocated to different parts of the plant (Cohen and Coffey, 1986), including the tubers. Liljeroth *et al.* (2016) found that phosphite residues are present in tuber tissue from plants treated with phosphite during the cropping season, even after several months of storage. Potassium phosphite integration with varieties has shown to have useful potential to suppress foliar blight in an integrated late blight disease management strategy. A review by Erwin and Ribeiro (1996) stated that phosphites had been used to control 19 species of *Phytophthora*. The result of this study revealed that there was substantial variance in the amount of foliar blight among different integration treatments in both seasons.

Interestingly, the relatively resistant and moderately resistant potato varieties combined with potassium phosphite performed better might be due to induced resistance by the salts. Therefore, based on the results of AUDPC, DPR, and PSI_f one can conclude that the effectiveness of the potassium phosphite and phosphate in combination with varieties is important for integrated disease management strategies i.e the lowest AUDPC is corresponding with the effective integration management of the late blight of potato. The combined treatments of potassium phosphites and relatively resistant and moderately resistant varieties might reduce the need for traditional fungicides and also decrease the selection pressure for fungicide resistance development in the pathogen populations. Tambascio *et al.* (2014) reported that the application of potassium phosphite to seed tubers reduced the time between planting and emergence and stimulated early growth under field conditions. They also found that mycorrhizal colonization increased after phosphite application of seed tubers. Increased tolerance to UV-B light as a response to phosphite application was reported by Oyarburo *et al*. (2015). Furthermore, pink rot of potato tubers, caused by *Phytophthora erythroseptica*, was reported to be controlled by potassium phosphite (Miller *et al*., 2006; Taylor *et al*., 2011). This evidence supports this study on the possibility of achieving broad benefits by incorporating potassium phosphite treatments into potato production systems.

Conclusions

In recent years, public demand for reduced pesticide use has been stimulated due to greater awareness of environmental and health issues as well as the development of fungicide resistant strains of pathogens. This concern has created the need to find alternatives to them. The findings in this study indicated that potassium phosphite and potassium phosphate had great inhibition effects against the infection and growth of the pathogen comparable to the recommended rate of fungicide Ridomil in the detached leaf assay. The potassium phosphite integrated into different varieties of potato revealed decreased late blight disease parameters like AUDPC, DPR and PSI and increased tuber yields of treated varieties. Potassium phosphite in combination with resistant varieties provided comparable control to recommended dose of fungicide Ridomil combination to varieties with increased tuber yields. Using phosphite might add other modes of action, including induced resistance, into late blight control strategies and significantly reduce the number of fungicides necessary for effective control. This could also reduce the selection pressure for the development of fungicide resistance in the pathogen population. Therefore, the results from the present study indicated that the combination of potassium phosphite with resistant and moderately resistant varieties could be a very useful component of integrated potato late blight disease management strategies. Additional investigation related to doses, intervals and combinations adjusted to the level of varietal resistance is needed; effects of environmental factors, and additive or synergistic effects with other chemical compounds. For the effectiveness and economics of potassium phosphite and fungicide spray, developing a disease forecasting model that assists the growers for spray schedule and reduces the costs involved by eliminating the unnecessary sprays and labor cost without increasing the risk of losing the crop is very important.

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