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Evaluation of the Reaction of Various Potato (*Solanum tuberosum* L.) Cultivars to the *Meloidogyne incognita* and *Ralstonia solanacearum* Disease Complex under Field Conditions

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Abstract

The performance of various potato cultivars in response to disease pressures from *Meloidogyne incognita* (MI) and *Ralstonia solanacearum* (RS) is believed to be different. The experiment was laid out in a randomised complete block design (RCBD) with three replications. A total of 13 potato cultivars during the main cropping season were assessed. The mean squares values from the analyses of variance for MI, RS, and plant parameters of potato cultivars at the two hot spot sites, '*Kersa*' and '*Arbarakate*' for the two pathogens showed highly significant ($P < 0.01$) differences among cultivars in terms of response to pathogens and plant parameters. At '*Kersa*', all of the tested potato cultivars were classed as 'moderately resistant'. However, '*Gudenie*' and '*Belete*' were classed as 'resistant' to RS. At '*Arbarakate*', '*Belete*', and '*Bubu*' were classed as 'resistant' to MI, while '*Gudenie*', '*Belete*', and '*Bubu*' were classed as 'resistant' to RS. At '*Kersa*', '*Gudenie*' recorded the highest mean values (25.5 t ha^{-1}) of marketable tuber yield (MY) and total yield (TY) (39.2 t ha^{-1}). At '*Arbarakate*', the highest mean value (49.6 t ha^{-1}) of TY was registered from the cultivar '*Bubu*'. TY had a negative phenotypic correlation with the pathogen's parameters but a positive with plant parameters. '*Gera*' was the most distant from all tested cultivars with Euclidean distance = 30.8. These assessments provide information for breeders for further improvement through selection.

Keywords Euclidean distance · Genotypic correlation · Location · Phenotypic correlation · Resistant

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Introduction

Potato (*Solanum tuberosum* L.) cultivars show resistance to some diseases and pests (Barrell et al. 2013); pests and diseases, such as the root-knot nematode (RKN; *Meloidogyne* spp.), still cause significant, up to 100%, yield losses, particularly in vegetable crop production (Onkendi et al. 2014; Seid et al. 2015). In Ethiopia, the occurrence of RKN has been reported on a small number of horticultural crops (Tefera and Hulluka 2000; Mandefro and Mekete 2002; Abegaz et al. 2019; Kassie 2019; Miheret et al. 2019; Seid et al. 2019). *Ralstonia solanacearum*, cause of bacterial wilt of *Solanaceae* crops, is another globally important destructive potato disease (EPPO 2020). Previously, the performances of various released and local potato cultivars in terms of plant yield and related parameters have been reported in Ethiopia (Berhanu and Tewodros 2016; Habtamu et al. 2016; Wassu 2016; Tessema et al. 2020). However, there is limited information on their performance in the presence of RKN and bacterial wilt disease complex. Crop losses are reported to be aggravated when RKN is found in association with bacterial wilt (Bekhiet et al. 2010; Shahbaz et al. 2015; Sundaresh et al. 2017).

The potato cultivars tested at different locations for resistance to the two diseases are believed to have genotypic and phenotypic correlation, genetic distance, and heritability differences. Estimates of heritability for different characters provide a picture of the amount of heritable variation present in different parameters (Johnson et al. 1955). The experiment was carried out to study the extent of association of genetic variability in potato cultivars for yield-related parameters and to find out the best cultivars for further use by farmers and in breeding programmes.

There is limited research information on the evaluation of potato cultivars' reaction to RKN and bacterial wilt disease complex at field conditions. The experiment aimed at evaluating potato cultivars for the two diseases helps to study the extent of association of genetic variability in potato cultivars for yield-related parameters and to find out the best cultivars for further use by farmers and in breeding programmes. The objectives of the present study were, therefore, to evaluate tuber yield performance, identify potential resistant potato cultivars to *Meloidogyne incognita* and *Ralstonia solanacearum* diseases complex, and group cultivars into different clusters to determine association yield, yield-related traits, and disease parameters.

Materials and Methods

Description of the Study Sites

Two farmer's fields that are known as hot spots for RKN and RS were selected based on the information generated from the survey conducted during the 2018 main cropping season. '*Kersa*' is located at an altitude of 1990 m.a.s.l., 09°15″N latitude, and 41°40″E longitude (SEHZOR 2006). The area is characterised by annual minimum and maximum temperatures of 12 and 24 °C, respectively, and

receives 780 mm of annual rainfall (EMA 2011). '*Arbarakate*' is located at an altitude of 2280 m.a.s.l., 9°14″N latitude, and 41°2″E longitude (SEHZOR 2006). The area is characterised by annual minimum and maximum temperatures of 12 and 23 °C, respectively, and receives 1150 mm of annual rainfall (EMA 2011).

Experimental Materials

A total of 13 potato cultivars recommended for cultivation under different agroecologies of the country between 1998 and 2013 were assessed. The cultivars were tested to be free from viral, wilt, and other plant diseases, and seed tubers were obtained from the Amhara Region Agricultural Research Institute (ARARI). The potato cultivars used in this study are shown in Table 1.

Experimental Procedures and Design

The experimental fields were prepared with a tractor to a depth of 25–30 cm, and ridges were prepared by hand. Plots measuring 4.5 m × 3.6 m consisting of six rows that could accommodate twelve plants at a spacing of 0.75 m between ridges and 0.30 m between plants, with spacing between plots and adjacent replicates of 1 and 1.5 m, respectively, were prepared for planting the potato cultivars during the main cropping season of 2020. Sprouted tubers measuring about 39 g were planted at the sides of ridges and at a depth of approximately 5 to 10 cm. The recommended rates

Table 1 Description of potato cultivars evaluated for tuber yield, yield-related traits, *Meloidogyne incognita*, and *Ralstonia solanacearum* disease complex parameters at two locations in eastern Ethiopia in 2020

Cultivar	Accession code	Year of release	Breeder/maintainer	Recommended altitude range for production m.a.s.l.
'*Chiro*'	AL-111	1998	Haramaya University	1700–2400
'*Bedassa*'	AL-114	2001	Haramaya University	1700–2400
'*Zengena*'	CIP-380479.6	2001	Adet ARC	2000–2800
'*Jalenie*'	CIP-37792.5	2002	Hawassa ARC/EIAR	1600–2800
'*Guassa*'	CIP-384321.9	2002	Adet ARC	2000–2800
'*Gera*'	KP-90134.2	2003	DebreBirhan ARC	2700–3200
'*Mara Charre*'	CIP-389701.3	2005	Hawassa ARC	1700–2700
'*Shonkolla*'	KP- 90,134.5	2005	Hawassa ARC/EIAR	1700–2700
'*Gudenie*'	CIP-386423.13	2006	Hawassa ARC/EIAR	1600–2800
'*Araarsaa*'	KP-90138.12	2006	Sinana ARC	2400–3350
'*Belete*'	CIP-393371.58	2009	Holeta ARC	1600–2800
'*Bubu*'	CIP-384321–3	2011	Haramaya University	1700–2000
'*Dagim*'	CIP-396004.337	2013	Adet ARC	1700–2700

Source: MoANR (2017). *ARC/EIAR*, Agricultural Research Center/Ethiopian Institute of Agricultural Research; *m.a.s.l.*, meter above sea level

of phosphorus at the rate of 100 kg P_2O_5 per ha in the form of diammonium phosphate were used, and the whole rate was applied (10 cm below the seed tuber) at planting. Nitrogen at the rate of 150 kg per ha was applied (7 to 10 cm away from the plant) in the form of urea in two splits: half rate after full emergence (2 weeks after planting) and half rate at the initiation of tubers (start of flowering). Weeding and other agronomic practices were performed as per normal crop management practices. The cultivars were harvested when the plants reached physiological maturity, as shown by yellowing or senescence on the lower leaves. The experiment was laid out in a randomised complete block design (RCBD) with three replications.

Nematode Identification

From each row, 90 days after planting, 10 g root system and 10 g tuber skin were collected, and female root-knot nematodes were stained with 1 ml acid fuchsine solution (3.5 g acid fuchsine/250 ml acetic acid and 750 ml distilled water) and then dislodged with a needle. The posterior portion of the female nematode was cut with a knife. The body contents were cleaned. The cleaned posterior portion was trimmed and transferred to a drop of glycerine on a clean microscopic slide and then observed under a stereomicroscope. *M. incognita* was identified from other *Meloidogyne* spp. based on the perennial pattern described by Taylor and Sasser (1978) and the morphology of the adult females (Eisenback and Hirschmann 1981).

Data Collection

The number of galls per root system and tuber (G/R) and the root system and tuber gall index (RGI) were recorded 90 days after planting. Root-gall index (RGI) was determined as described by Taylor and Sasser (1978). Resistance/susceptibility of the cultivars to RKN was scored using ratings depicted by Pederson and Windham (1989). $RGI = [\sum (Si \times Ni) \div (N \times 5)] \times 100$; where Si is root and tuber galling scale of 0, 1, 2, 3, 4, 5, where 0 = no galls; 1 = 1 or 2, 2 = 3–10; 3 = 11–30; 4 = 31–100; 5 > 100. Ni is the number of plants in each root and tuber galling scale. Nis the total number of evaluated plants. From these figures, the resistance/susceptibility was scored using the following system: Immune RGI = 0; highly resistant $0.1 \leq RGI \leq 5.0$; resistant $5.1 \leq RGI \leq 25.0$; moderately susceptible $25.1 \leq RGI \leq 50.0$; susceptible $50.1 \leq RGI \leq 75.0$; highly susceptible RGI > 75.0. Root system and tuber were rated for galling severity on a 0 to 4 scale, where 0 = no galling (0%), 1 = light galling (1–25%), 2 = moderate galling (26–50%), 3 = heavy galling (51–75%), 4 = severe galling (76–100% galled root system and tuber) according to Barker (1985).

Resistance/susceptibility of the cultivars to bacterial wilt was scored using indices described by Winstead and Kelman (1952). Bacterial wilt index $(BWI) = \sum (ni \times vi) \div (V \times N)$; where the ni = number of plants with the respective disease rating; vi = disease rating: 0 = no wilting, 1 = < 10% wilted plants, 2 = 11–25% wilted plants, 3 = 26–50% wilted plants, 4 = 51–75% wilted plants, 5 = > 75% wilted plants; V = the highest disease rating (5); N = the number of plants observed. Highly resistant (BWI = 0.0–0.2), resistant (BWI = 0.2–0.3), moderately resistant (BWI = 0.31–0.4),

moderately susceptible (BWI = 0.41–0.5), susceptible (BWI = 0.51–0.60), highly susceptible (BWI = 0.61–0.9), extremely susceptible (BWI = 0.91–1.0).

Marketable tuber number per plant (MTNPP), unmarketable tuber number per plant (UMTNPP), average tuber weight (ATW in *g*), marketable yield (MY; number of MTNPP * ATW/plot area), unmarketable yield (UMY), and total tuber yield (TY in t ha^{-1})) were recorded 90 days after planting.

Data Analysis

All the *M. incognita*, *Ralstonia solanacearum*, and plant-related data from each location were subjected to analysis of variance (ANOVA) using RCBD. The error variance homogeneity test was conducted using *F*-ratio, before the combined ANOVA over locations was conducted for each parameter. Some of the data were transformed using log $(x+1)$. The mean performances of cultivars were compared based on pooled means over locations using Duncan multiple range test (DMRT) at $P \leq 0.05$ depending on the results of each location and over-location ANOVA and error variance homogeneity test. All analyses were computed using SAS software version 9.2.

The genetic distance of potato cultivars was estimated using Euclidean distance (ED) calculated from data collected from field experiments after standardisation (subtracting the mean value and dividing it by the standard deviation) as established by Sneath and Sokal (1973) as follows:

$$\mathrm{EDjk} = \sqrt{\sum_{i=1}^{n} (Xij - Xik)^2}^{2}$$

EDjk = distance between cultivars *j* and *k*; *Xij* and *Xik* = pathogens and plant-related parameter values of the i^{th} character for cultivars *j* and *k*, respectively; *n* = number of parameters used to calculate the distance. The distance matrix from pathogen and plant-related parameters was used to construct a dendrogram based on the unweighted pair-group method with arithmetic means. The results of cluster analysis were presented in the form of a dendrogram.

Phenotypic and Genotypic Correlation Coefficients

Phenotypic (r_p) and genotypic (r_g) correlations between two parameters were estimated using the formula suggested by Johnson et al. (1955); Singh and Chaudhry (1985).

$$rpxy = \frac{COVpxy}{\sqrt{\sigma^2 px.\sigma^2 py}}$$

rpxy = phenotypic correlation coefficient between character *x* and *y*; *COVpxy* = phenotypic covariance between character *x* and *y*; $\sigma^2 px$ = phenotypic variance for character *x*; $\sigma^2 py$ = phenotypic variance for character *y*.

$$rgxy = \frac{COVgxy}{\sqrt{\sigma^2 gx.\sigma^2 gy}}$$

where *rgxy* = genotypic correlation coefficient between character *x* and *y*; *COVgxy* = genotypic covariance between character *x* and *y*; $\sigma^2 gx$ = genotypic variance for character *x*; $\sigma^2 gy$ = genotypic variance for character *y*. The coefficient of correlation at the phenotypic level was tested for significance by comparing the values of correlation coefficient (*r*) with tabulated *r*-value at *g* - 2 degrees of freedom, where *g* is a number of genotypes/cultivars. However, the coefficient of correlations at the genotypic level was tested for significance using the formula described by Robertson (1959).

$$t = \frac{(rgxy)}{SErgxy}$$

The calculated *t* value was compared with the tabulated *t* value at *g* - 2 degrees of freedom at a 5% level of significance, where *g* = number of genotypes, *rgxy* = genotypic correlation coefficient, and SE_{rgxy} = standard error of genotypic correlation coefficient between character *x* and *y*, which were calculated as

$$SE_{r_{gxy}} = \sqrt{\frac{(1 - r^2)^2}{2H^2{}_x.H^2_y}}$$

$H^2{}_x$ = heritability value of character *x*, and $H^2 y$ = heritability value of character *y*. Broad sense heritability ($H^2 b$) was estimated by the formula suggested by Johnson et al. (1955). Low (0–30%), medium (31–60%), and high (61% and above). $H^2 b = (\sigma^2 g/\sigma^2 p)*100$; where $\sigma^2 g$ = genotypic variance and $\sigma^2 p$ = phenotypic variance.

Results

Mean Performance of the Potato Cultivars

The mean square values for *Meloidogyne incognita* (MI), *Ralstonia solanacearum* (RS), and plant-related parameters/traits of potato cultivars at '*Kersa*' and '*Arbarakate*' showed highly significant ($P < 0.01$) differences among cultivars on the number of galls per root system and tuber (G/R), root and tuber gall index (RGI), and bacterial wilt index (BWI). It also showed highly significant differences in marketable tuber number per plant (MTNPP), unmarketable tuber number per plant (UMTNPP), average tuber weight (ATW), marketable yield (MY), unmarketable yield (UMY), and total yield (TY), except RGI and ATW in '*Kersa*', which showed nonsignificant differences.

The mean squares from combined analysis of variance for MI, RS, and plant parameters of cultivars tested at the two locations revealed the presence of highly significant differences among the cultivars, except for parameter RGI, which showed nonsignificant differences. It also exhibited the absence of a significant difference between the locations except for BWI. However, the cultivar and location interactions showed highly significant differences in BWI and UMTNPP (Table 2). At '*Kersa*','*Gudenie*', '*Belete*', and '*Bubu*' showed the lowest mean values of G/R (19.3, 16.3, and 16) and RGI each 3.0, respectively, but '*Shonkolla*' had the highest G/R (35.3) and RGI (4.0), respectively. Among all the tested cultivars, '*Belete*' registered the lowest mean values (0.23) of BWI, but '*Shonkolla*' had the highest mean values (0.83) of the parameter.

At '*Arbarakate*', '*Bubu*' registered the lowest G/R (9.3) and RGI (2.3), but '*Jalenie*' had the highest G/R (27.3). At this location, '*Belete*' showed the lowest (0.20), while '*Gera'* showed the highest mean value (0.57) of BWI (Table 3).

At '*Kersa*', the galling severity of all cultivars ranged from light galling to moderate galling. '*Gudenie*', '*Mara Charre*', '*Belete*', and '*Bubu*' showed light galling. The other cultivars all showed moderate galling. None of the tested cultivars was 'resistant' to MI in this location. '*Chiro*' was classed as 'moderately susceptible' while the others were classed as 'moderately resistant'. Only '*Gudenie*' and '*Belete*' were classed as 'resistant' to RS. The other cultivars categorised were classed as 'moderately susceptible' to 'highly susceptible'.

At '*Arbarakate*', the severity of the galls seen on all cultivars was classed as light galling. '*Belete*' and '*Bubu*' were classed as 'resistant', while the other cultivars were classed as 'moderately resistant' to the MI. Only '*Gudenie*', '*Belete*', and '*Bubu*' were classed as 'resistant' to RS, while '*Gera*' and '*Araarsaa*' were 'susceptible'. The other cultivars were classed as 'moderately susceptible' to RS (Table 4).

At '*Kersa*', '*Gudenie*' and '*Guassa*' produced the highest mean value (9.3) of MTNPP. However, '*Araarsaa*', '*Dagim*', and '*Zengena*' produced the lowest mean value of this parameter (4.0). On the other hand, '*Gudenie*' registered the highest mean value (4.6) of UMTNPP, but '*Chiro*' and '*Bedassa*' produced the lowest value (2.0) of this parameter. '*Bubu*' produced the highest mean value (62.3 g) of the ATW, but '*Gera*' had the lowest (45.0 g). '*Gudenie*' recorded the highest mean value (25.5 t ha^{-1}) of MY. However, '*Araarsaa*', '*Dagim*', and '*Zengena*' produced the lowest mean values for this parameter. '*Gudenie*' produced the highest TY (39.2 t ha^{-1}), but '*Araarsaa*', '*Bedassa*', '*Dagim*', and '*Zengena*' produced the statistically lowest mean values (17.5–19.6 t ha^{-1}) of TY.

At '*Arbarakate*', '*Chiro*' generated the highest mean value (68.3 g) of ATW, while '*Gera*' recorded the lowest value (40.6 g). '*Chiro*', '*Gudenie*', '*Jalenie*', and '*Bubu*' produced higher mean values that ranged from 33.5 to 37.5 for MY t ha^{-1}, but '*Gera*', '*Araarsaa*', '*Bedassa*', '*Dagim*', and '*Zengena*' produced lower values (18.6–22.5 t ha^{-1}) for this parameter. At this location, the highest mean value (49.6 t ha^{-1}) of TY was registered in '*Bubu*', however '*Gera*', '*Bedassa*', and '*Dagim*' produced lower values of the parameter (Table 4).

Table 2 Mean squares from combined analysis of variance '*Kersa*' and '*Arbarakate*' for *Meloidogyne incognita*, *Ralstonia solanacearum*, and plant-related parameters of potato cultivars evaluated in 2020

Parameter	Replication (2)	Cultivar (12)	Location (1)	Cultivar × location (12)	Error (50)	CV (%)
Number of galls per root system and tuber	19.44	97.04**	2.13 ns	4.94 ns	3.27	7.86
Root system and tuber gall index	0.01	0.16 ns	0.03 ns	0.05 ns	0.05	7.89
Bacterial wilt index	0.01	0.03**	0.00**	0.00**	0.00	20.20
Marketable tuber number per plant	0.64	9.70**	0.05 ns	0.12 ns	0.30	6.81
Unmarketable tuber number per plant	0.01	1.56**	0.00 ns	0.18**	0.01	4.07
Average tuber weight (g)	37.78	94.50**	0.09 ns	24.15*	3.49	3.28
Marketable tuber yield (t ha^{-1})	25.80	106.20**	0.39 ns	5.11*	1.16	4.70
Unmarketable tuber yield (t ha^{-1})	0.20 (1.00)	15.17** (0.03**)	0.14 ns (0.01**)	1.60 ns (1.00**)	0.25 (0.00)	5.70 (3.16)
Total tuber yield (t ha^{-1})	30.60	178.00**	0.06 ns	5.50*	1.19	3.42

ns, nonsignificant. * and **, significant at $P<0.05$ and $P<0.01$, respectively. CV (%) = percentage of coefficient of variation. Values of unmarketable tube yield in the parenthesis are the transformed data

Table 3 Mean of gall per root system and tuber, galling index, and bacterial wilt index for 13 potato cultivars evaluated at two locations during the 2020 cropping season

Cultivar	Number of galls per root system and tuber			Root system and tuber gall index			Bacterial wilt index		
	Kersa	Arbarakate	Pooled mean	Kersa	Arbarakate	Pooled mean	Kersa	Arbarakate	Pooled mean
'*Chiro*'	31.60abc	23.30abc	27.45	3.60ab	3.00a	3.30	0.60b	0.47b	0.54
'*Gudenie*'	19.30e	13.30efg	16.30	3.00b	3.00a	3.00	0.28 h	0.23 g	0.26
'*Mara Charre*'	25.30d	15.60def	20.45	3.00b	3.00a	3.00	0.52d	0.50c	0.51
'*Jalenie*'	33.60ab	27.30a	30.45	3.60ab	3.00a	3.30	0.60b	0.50c	0.55
'*Guassa*'	29.60a–d	22.00a–d	25.80	3.30ab	3.00a	3.15	0.50e	0.43e	0.47
'*Gera*'	29.60a–d	21.00a–d	25.30	3.30ab	3.00a	3.15	0.57c	0.57a	0.57
'*Araarsaa*'	30.60a–d	25.30ab	27.95	3.30ab	3.00a	3.15	0.57c	0.53b	0.55
'*Belete*'	16.30e	9.60 fg	12.95	3.00b	2.30b	2.65	0.23i	0.20 h	0.22
'*Bedassa*'	25.60d	19.60bcd	22.60	3.00b	3.00a	3.00	0.50e	0.43e	0.47
'*Bubu*'	16.00e	9.30 g	12.65	3.00b	2.30b	2.65	0.43 g	0.30f	0.37
'*Dagim*'	29.30bcd	21.00a–d	25.15	3.30ab	3.00a	3.15	0.47f	0.43d	0.45
'*Shonkolla*'	35.30a	23.60abc	29.45	4.00a	3.00a	3.50	0.83a	0.47d	0.65
'*Zengena*'	26.60 cd	18.00cde	22.30	3.00b	3.00a	3.00	0.60b	0.50c	0.55

Mean values sharing common letter(s) within columns did not differ significantly at $P \leq 0.05$ according to Duncan multiple range test (DMRT)

Table 4 Mean values of marketable tuber number per plant, unmarketable tuber number per plant, average tuber weight, marketable yield, unmarketable yield, and total tuber yield of 13 potato cultivars tested during 2020 cropping season at '*Kersa*' and '*Arbarakate*'

Cultivar	MTNPP	UMTNPP	ATW	MY	UMY	TY	Pooled mean	MTNPP	UMTNPP	ATW	MY	UMY	TY	Pooled mean
	'*Kersa*'							'*Arbarakate*'						
'*Chiro*'	7.00bc	2.00c	60.60ab	20.60ab	6.00ef	26.70 cd	20.50	10.00ab	2.00b	68.30a	33.50a	6.60ef	40.20bc	26.80
'*Gudenie*'	9.30a	4.60a	56.30abc	25.50a	13.70a	39.20a	24.80	11.30a	3.60a	62.30abc	34.50a	11.10ab	45.60ab	28.10
'*Mara Charre*'	7.60abc	3.60ab	49.00abc	18.40bc	8.10de	26.60 cd	18.90	11.30a	3.00ab	54.60c	30.40ab	8.00de	38.40bcd	24.30
'*Jalenie*'	7.60abc	3.00bc	59.60ab	22.40ab	8.30de	30.70bc	21.90	11.30a	3.00ab	61.60abc	34.20a	9.00 cd	43.30ab	27.10
'*Guassa*'	9.30a	4.00ab	48.30bc	21.90ab	11.20abc	33.50ab	21.40	10.60ab	4.00a	60.30abc	31.50ab	11.80a	43.30ab	26.90
'*Gera*'	6.00 cd	4.00ab	45.00c	13.20 cd	8.20de	21.40de	16.30	9.300b	4.00a	40.60d	18.60c	7.90de	26.60f	17.80
'*Araarsaa*'	4.00e	3.00bc	58.60ab	11.40d	8.10de	19.60e	17.50	7.30c	3.00ab	62.60abc	22.50c	9.20 cd	31.70def	22.70
'*Belete*'	8.00ab	4.00ab	58.30ab	22.80ab	10.80bcd	33.70ab	25.90	11.30a	4.00a	56.60bc	31.50ab	11.10ab	42.60ab	26.20
'*Bedassa*'	4.60de	2.00c	53.60abc	12.20 cd	4.90f	17.20e	15.80	7.30c	2.00b	57.60abc	20.70c	5.60f	26.40f	19.90
'*Bubu*'	8.00ab	4.00ab	62.30a	24.10ab	12.60ab	36.80ab	24.60	11.30a	3.60a	67.60ab	37.50a	12.10a	49.60a	30.30
'*Dagim*'	4.00e	3.30b	51.60abc	10.10d	7.80e	18.00e	15.80	7.30c	2.00b	56.60bc	20.40c	5.50f	25.90f	19.60
'*Shonkolla*'	6.00 cd	3.00bc	61.60ab	18.30bc	8.70cde	27.00 cd	20.80	9.30b	4.00a	54.30c	25.00bc	9.70bc	34.70cde	22.80
'*Zengena*'	4.00e	3.00bc	52.30abc	10.20d	7.20ef	17.50e	15.70	7.30c	3.30a	54.60c	19.70c	8.80 cd	28.50ef	20.40

Mean values sharing common letter(s) within columns did not differ significantly at $P \leq 0.05$ according to Duncan multiple range test (DMRT). *MTNPP*, marketable tuber number per plant; *UMTNPP*, unmarketable tuber number per plant; *ATW*, average tuber weight in g; *MY*, marketable yield in t ha^{-1}; *UMY*, unmarketable yield in t ha^{-1}; *TY*, total yield in t ha^{-1}

Genotypic and Phenotypic Correlations

Genotypic correlation coefficients were computed for MI, RS, and plant-related parameters. The results revealed a positive and highly significant genetic correlation between G/R and BWI (rg = 0.74). However, G/R had negative and highly significant correlations (rg = − 0.43) with UMY. G/R also had a negative but significant genetic correlation with the other plant parameters studied. RGI had a positive and significant genetic correlation (rg = 0.53) with BWI. ATW, MY, and UMY had positive and significant genetic correlations with TY.

A positive and highly significant phenotypic correlation (rp = 0.74) was observed between G/R and BWI. MTNPP showed a negative but highly significant phenotypic correlation with G/R and RGI. UMTNPP had a negative and highly significant phenotypic correlation with MTNPP (rp = − 0.83). MY showed a positive and highly significant phenotypic correlation with ATW (rp = 0.91) but a negative and highly significant correlation with UMY. Generally, TY had a negative phenotypic correlation with the pathogen parameters, but this was positive with all plant-related parameters studied (Table 5).

Genetic Distance

'*Gera*' was the most distant from all tested cultivars with ED = 30.87. '*Gudenie*' was found to be distant from most of the cultivars except from '*Belete*' (ED = 7.62) and '*Bubu*' (ED = 7.48). '*Jalenie*' was found to be distant from most of the tested cultivars except from '*Shonkolla*' (ED = 6.48). '*Dagim*' was the closest to '*Zengena*' with ED = 2.45 (Table 6).

Table 5 Genotypic (above diagonal) and phenotypic (below diagonal) correlation coefficients for *Meloidogyne incognita*, *Ralstonia solanacearum*, and plant-related parameters in 13 potato cultivars performed during 2020 cropping season

Parameters	G/R	RGI	BWI	MTNPP	UMTNPP	ATW	MY	UMY	TY
G/R		0.69**	0.74**	−0.26*	−0.38*	−0.03	−0.26*	−0.43**	−0.35*
RGI	0.53*		0.53*	−0.04	−0.15*	−0.18*	−0.04	−0.09*	0.00
BWI	0.74**	0.53*		−0.38*	−0.47**	−0.09*	−0.32*	−0.47**	−0.41*
MTNPP	−0.28**	−0.05**	−0.38*		−0.46**	0.38*	0.89**	0.60**	0.19*
UMTNPP	−0.41**	−0.20**	−0.47*	−0.83**		−0.03	0.35*	0.85**	0.15*
ATW	−0.03	−0.23**	−0.09	−0.03	0.84**		0.70*	0.43*	0.67**
MY	−0.29*	0.05**	−0.32*	0.30*	0.60**	0.91**		−0.65*	0.95**
UMY	0.47**	0.12**	0.47*	0.72**	0.37*	0.61**	−0.85**		0.78**
TY	−0.38*	0.00	−0.41*	0.84**	0.45*	0.58*	0.89**	0.69**	

* and ** = significant at $P < 0.05$ and $P < 0.01$, respectively. *G/R*, number of galls per root system and tuber; *RGI*, root system and tuber gall index; *BWI*, bacterial wilt index; *MTNPP*, marketable tuber number per plant; *UMTNPP*, unmarketable tuber number per plant; *ATW*, average tuber weight; *MY*, marketable yield; *UMY*, unmarketable yield; *TY*, total yield

Table 6 Euclidean distance of 13 potato cultivars measured from *Meloidogyne incognita*, *Ralstonia solanacearum*, and plant-related parameters and means Euclidean distance attained by averaging each cultivars distance to other 12 cultivars

Cultivars	'*Gudenie*'	'*MaraCharre*'	'*Jalenie*'	'*Guassa*'	'*Gera*'	'*Araarsa*'	'*Belete*'	'*Bedasa*'	'*Bubu*'	'*Dagim*'	'*Shonkola*'	'*Zengena*'
'*Chiro*'	21.02	14.56	5.29	16.06	19.24	13.00	18.71	16.52	20.54	17.55	5.48	17.89
'*Gudenie*'		18.22	19.08	15.36	27.96	28.37	7.62	28.97	7.48	29.63	23.24	29.26
'*MaraCharre*'			15.36	10.10	10.30	15.84	15.68	13.60	20.30	13.71	16.61	13.27
'*Jalenie*'				13.49	20.69	16.40	18.71	20.42	19.90	20.49	6.48	21.07
'*Guassa*'					16.67	21.79	17.26	22.29	20.25	21.26	17.38	21.63
'*Gera*'						14.39	25.46	11.36	30.87	8.60	19.44	9.06
'*Araarsaa*'							24.35	8.49	27.11	7.68	11.36	8.43
'*Belete*'								23.98	5.48	25.61	21.49	24.82
'*Bedassa*'									28.02	5.39	17.35	4.12
'*Bubu*'										29.46	22.80	28.84
'*Dagim*'											16.97	2.45
'*Shonkolla*'												17.83

Clustering of Potato Cultivars

The tested potato cultivars were clustered into five based on Euclidean distance. Cluster I consisted of three cultivars ('*Dagim*', '*Zengena*', and '*Bedassa*') characterised by low yield. Cluster II consisted of two cultivars ('*Araarsaa*' and '*Gera*'), cluster III ('*Chiro*', '*Jalenie*', and '*Shonkolla*'), and cluster IV ('*Mara Charre*' and '*Guassa*'). The last (cluster V) showed resistance to MI and RS and had a high yield consisting of '*Belete*', '*Bubu*', and '*Gudenie*' (Fig. 1).

Clusters III and V registered the highest and lowest mean values (33.5 and 17.2, respectively) of the number of galls per root system and tuber. These clusters also registered the highest and lowest mean values (0.67 and 0.31, respectively) of bacterial wilt index. Clusters I and V recorded the lowest and highest mean values (10.8 and 24.1 t ha^{-1}), respectively, of marketable tuber yield. The clusters also registered the lowest and highest mean values (6.6 and 12.3 t ha^{-1}) of unmarketable tuber yield and 17.1 and 36.5 t ha^{-1} of total tuber yield, respectively (Table 7).

Heritability of the Parameters

The heritability (H_2b) in a broad sense for all parameters studied was computed and categorised as suggested by Johnson et al. (1955). Accordingly, the RGI and

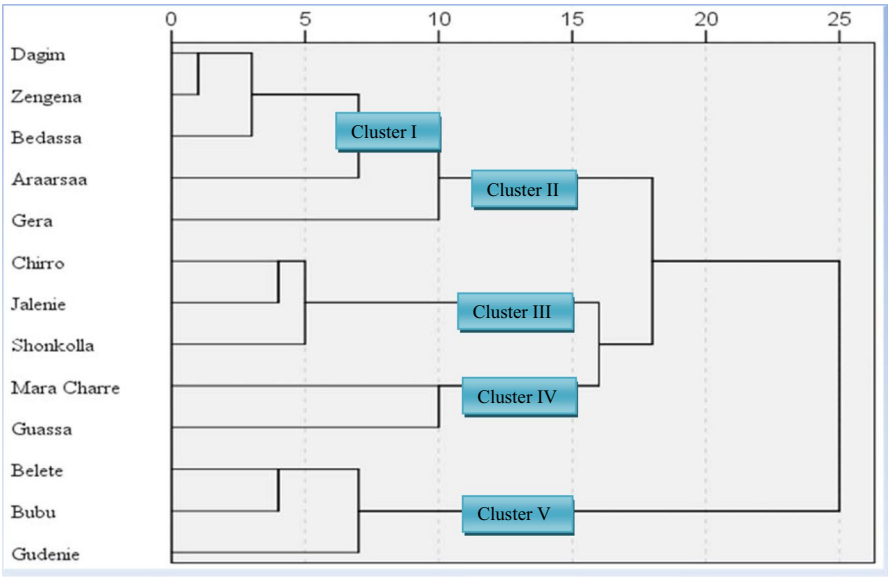

Fig. 1 Dendrogram showing the genetic relationship among 13 potato cultivars based on *Meloidogyne incognita*, *Ralstonia solanacearum*, and plant-related parameters. The numbers (0–25) show a dissimilarity matrix

Table 7 Mean values of five clusters of 13 potato cultivars for *Meloidogyne incognita*, *Ralstonia solanacearum*, and plant-related parameters

Parameter	Cluster I	Cluster II	Cluster III	Cluster IV	Cluster V	Overall mean
Number of galls per root system and tuber	27.16	30.10	33.50	27.5	17.20	27.00
Bacterial wilt index	0.52	0.57	0.67	0.51	0.31	0.51
Marketable tuber number per plant	4.20	5.00	6.80	8.45	8.40	6.50
Unmarketable tuber number per plant	2.70	3.50	2.60	3.80	4.20	3.36
Average tuber weight (g)	52.50	51.80	60.60	48.70	58.90	54.50
Marketable tuber yield (t ha^{-1})	10.80	12.30	20.40	20.10	24.10	17.50
Unmarketable tuber yield (t ha^{-1})	6.60	8.10	7.60	9.70	12.30	8.70
Total tuber yield (t ha^{-1})	17.20	20.50	28.10	31.00	36.50	26.60

ATW fell under the medium category, while the rest of the parameters fell under high in '*Kersa*'. All the parameters from '*Arbarakate*' fell under the high H_2b category (Table 8).

Discussion

The mean square values from the analyses of variance for MI, RS, and plant-related parameters of potato cultivars at '*Kersa*' and '*Arbarakate*' showed highly significant differences among all parameters, indicating the influence of environment on the parameters and the presence of genetic variability in the tested potato cultivars.

Table 8 The heritability study of the parameters at '*Kersa*' and '*Arbarakate*' during the 2020 cropping season

	'*Kersa*'		*'Arbarakate'*	
Parameter	Heritability	Category	Heritability	Category
Number of galls per root system and tuber	0.83	High	0.77	High
Root gall index	0.56	Medium	0.67	High
Bacterial wilt index	1.00	High	0.97	High
Marketable tuber number per plant	0.82	High	0.86	High
Unmarketable tuber number per plant	0.73	High	0.73	High
Average tuber weight (g)	0.57	Medium	0.68	High
Marketable tuber yield (t ha^{-1})	0.76	High	0.78	High
Unmarketable tuber yield (t ha^{-1})	0.97	High	0.87	High
Total tuber yield (t ha^{-1})	0.83	High	0.82	High

UMTNPP, ATW, MY, and TY were significantly influenced by cultivar and cultivars × location interaction, evidencing the various responses of the cultivars across locations. Significant effects of cultivars, location, and their interaction on the yield parameters of potato cultivars have been reported in Ethiopia (Berhanu and Tewodros 2016; Wassu 2016; Tessema et al. 2020). The presence of significant differences among released potato cultivars for MY and TY has been reported in Ethiopia (Habtamu et al. 2016; Tessema et al. 2020). Wassu (2016) also reported the presence of significant differences among 16 released potato cultivars for MY, TY, and late blight disease resistance in Ethiopia.

At '*Kersa*', '*Gudenie*' and '*Guassa*' produced the highest MTNPP. '*Bubu*' produced the highest ATW. At '*Arbarakate*', in most cultivars, higher MTNPP was recorded. '*Chiro*' generated the highest ATW. Previously, significant differences among potato cultivars and their growing environments for MTNPP and ATW were reported by Berhanu and Tewodros (2016), Habtamu et al. (2016), Seifu and Betewulign (2017), and Tessema et al. (2020). Eaton et al. (2017) reported that genetic variation among cultivars, management practice, or agroecological conditions could contribute to the variations in performance among potato cultivars.

Significant differences among potato cultivars in their reaction to RKN have been reported, with the 'highly resistant' cultivars containing fewer developed nematodes than 'susceptible' cultivars (Bekhiet et al. 2010; Hussain et al. 2016; Montasser et al. 2019; Getu et al. 2021). At '*Kersa*', '*Gudenie*', '*Mara Charre*', '*Belete*', and '*Bubu*' showed light galling, while comparisons with the results from the other cultivars showed that the tested potato cultivars had genetic variability for this trait. At this location, none of the tested cultivars was resistant to MI.

Heritability estimates provide information about the likelihood that a particular genetic attribute will be transmitted to the successive generation (Marwede et al. 2004). The H_2b for all parameters studied was computed. Accordingly, at '*Kersa*', ATW falls under medium, while the other parameters are grouped under high. All parameters from '*Arbarakate*' grouped under high H_2b, suggesting that the parameters tested could be further improved through selection. Plant parameters that have high H_2b are likely to be favourable targets in plant breeding programmes for developing better potato cultivars.

When two parameters are highly genetically correlated, the genes that contribute to the parameters are usually co-inherited (Lynch and Walsh 1998). In the current study, genotypic and phenotypic correlation coefficients were computed for MI, RS, and plant-related parameters. The coexistence of the two pathogens has been reported by many workers on various hosts (Bekhiet et al. 2010; Ghosh et al. 2016; Sundaresh et al. 2017). G/R and BWI had negative and highly significant correlations with unmarketable tuber yield. This suggests that MI and RS disease complex is linked to unmarketable tuber yield but adversely impact marketable tuber yield.

The Euclidean distance is a measure of dissimilarity in both morphological and molecular analyses. Dissimilarity coefficients estimate the distance or unlikeness of two individuals; the larger the value, the more different are the two individuals (Persson 2001). Populations with many similar genes have small genetic distances (Osawaru et al. 2015). In the present work, '*Gera*', which fell under 'moderately resistant' and 'susceptible' to MI and RS, respectively, was

the most distant from all tested cultivars. This implies this cultivar was the most different to the other tested potato cultivars. '*Gudenie*' was found to be close to '*Belete*' and '*Bubu*', suggesting that they are closely related and/or have a recent common ancestor.

In a cluster analysis, relatively homogeneous groups of individuals cluster together hierarchically, and this clustering is displayed in a dendrogram (Holland 2006; Osawaru et al. 2015). In this study, '*Dagim*', '*Zengena*', and '*Bedassa*', which were characterised by low yield, have been clustered together, whereas '*Belete*', '*Bubu*', and '*Gudenie*' resistant to MI, RS, and which showed higher yields, were clustered together. This suggests the cultivars within a cluster were homogeneous.

Conclusions

From the present study, it can be concluded that all potato cultivars assessed performed differently in terms of their reactions to *Meloidogyne incognita*, *Ralstonia solanacearum*, and yield-related parameters. A significant interaction between the cultivars and locations was seen. Positive and highly significant genotypic and phenotypic correlations were recorded between MI and RS. The pathogens had negative and highly significant correlations with the studied plant-related parameters. At '*Kersa*', '*Gudenie*' recorded the highest mean value (25.5 t ha^{-1}) of marketable yield. At '*Arbarakate*', '*Chiro*', '*Gudenie*', '*Jalenie*', and '*Bubu*' produced higher mean values that ranged from 33.5 to 37.5 t ha^{-1} for this parameter. These data provide information for breeders for further improvement through selection since most of the studied parameters were shown to be heritable.

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Data Availability Raw data were generated at Haramaya University. Derived data supporting the findings of this study are available from the corresponding author [Tasew Getu] on demand.

Code Availability Not applicable.

Declarations

Conflict of Interest The authors declare no competing interests.

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