Research Article

Evaluation of Irrigation Methods, Potato Cultivars and Vermicompost for Integrated Management of the *Meloidogyne incognita* and *Ralstonia solanacearum* Disease Complex

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Abstract | The *Meloidogyne incognita* (MI) and *Ralstonia solanacearum* (RS) disease complex is considered among the most important potato yield-limiting factors. This research was conducted to evaluate the effect of irrigation methods, cultivars, vermicompost (VC) and their interactions for management of the MI and RS disease complex under field conditions. The experiment was laid out in a split-split plot design with three replications. The findings indicated that the treatments and their interactions significantly ($P \leq 0.05$) affected the development of MI, RS, and impacted potato yield. The cultivar *Gudenie* had the lowest mean value (2.2) of MI reproduction factor with drip irrigation amended with VC. *Belete* registered the lowest mean values of galls (6.6) and eggmasses (7.0) per root system and tuber, and RS final colonies (2.6×10^5) with same treatment. The presence of VC greatly increased tuber yield, and *Guassa* and *Bubu* produced the highest marketable tuber yield of 47 and 48 t/ha, respectively under this treatment. All cultivars that were grown with drip irrigation amended with VC fell into the resistant category towards MI and RS disease complex. The study revealed that the tested treatments respond differently to the disease complex, and potato yield parameters. Therefore, the integration of drip irrigation, VC and selected cultivars could be used for sustainable management of MI and RS infections in potato production during the dry season.

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Introduction

Potato has been widely described as global food and nutritional security option particularly for the poor people (Singh and Rana, 2013). Potato's nutritional value is higher than most of the food crops. It is considered as the richest source of carbohydrates (Ali *et al*., 2015). In addition, the high cash rewards encouraged farmers to be involved in potato production (Elraiah *et al*., 2014). In Ethiopia, potato is one of the cash crops that plays a significant role in improving farmers' income and food security (Haverkort *et al*., 2012; Devaux *et al*., 2020). Potato production, however, is constrained by diseases and pests, lack of appropriate cultivars with grower desired traits, and soil infertility (Edgar *et al*., 2010).

The root-knot nematodes (RKN; *Meloidogyne* spp.) are members of the genus *Meloidogyne* Goldi (1892), *Meloidogyne* is of Greek origin and means apple-shaped female (Moens *et al*., 2009). They are sedentary endoparasites that are highly polyphagous, globally distributed pests that can cause up to 100% yield losses particularly on 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 (Abegaz *et al*., 2019; Kassie, 2019; Mandefro and Mekete, 2002; Miheret *et al*., 2019; Seid *et al*., 2019; Tefera and Hulluka, 2000). Seid *et al*. (2019) reported the occurrence of the four major RKN species, *Meloidogyne incognita*, *M. javanica, M. arenaria*, and *M. hapla* on tomato, using DNA and protein-based identification techniques. Of the RKN species studied to date, *M. incognita* is the most significant pathogen and is widely distributed in tomato cultivation areas in Ethiopia (Seid *et al*., 2019). However, there is limited research on its management in this region.

Ralstonia solanacearum (bacterial wilt) is among the most destructive potato diseases globally (EPPO, 2020). Yield losses of 30 to 100% due to *R. solanacearum* were reported in Kenya and Uganda (Kinyua *et al*., 2005). In Ethiopia, *R. solanacearum* has been detected on potatoin many parts of the country including Kefa, Gamugofa, Sidamo, Shashemane, Holetta, Welega, Welo, Shewa, Arsi, Haramaya, Kersa, Gojam, and Tigray (Abdurahman *et al*., 2017; Gebremedhin *et al*., 2006; Henok *et al*., 2007; Kassa 1996; Lemessa and Zeller 2007; Tessema *et al*., 2020). The synergistic interaction between RKN and *R. solanacearum* on various hosts is widely recognized (Ateka *et al*., 2001; Martin and Nydegger, 1982; Pavithra *et al*., 2014; Sundaresh *et al*., 2017). Crop losses are reported to be more aggravated when RKN is present in association with *R. solanacearum* (Bekhiet *et al*., 2010; Shahbaz *et al*., 2015; Sundaresh *et al*., 2017). In Ethiopia, research information on the management of disease complexes on crops, including potato, is limited.

Management methods using agrochemicals have not been found to be economical in Ethiopian cropping systems and also show toxic effects on a plant, soil, and ground water (Jatala and Martin, 1977; Karimi *et al*., 2017). Thus, for RKN and *R. solanacearum* management, it is critical to explore environ mentally friendly alternative approaches. Irrigation is the process of applying water to the soil, primarily to meet the water needs of growing plants. There are three main irrigation methods. Drip irrigation is a method in which water is applied drop by drop directly to the soil overlying the roots. Sprinkler irrigation is similar to natural rainfall where water is pumped through a pipe system and then sprayed onto the crops through rotating sprinkler heads (Shock, 2013). The sub-irrigation/ furrow method is where the water table is raised to or held near the plant root zone using ditches or subsurface drains to supply the water (Bjorneberg, 2013). Drip irrigation has been reported to reduce the transmission of pathogens, reduces water use (80–95%), nitrate leaching, and erosion, increasing marketable yield while sprinkler and furrow irrigated fields are subject to greening or sunscaldand are more susceptible to early and late blight pathogens (Dasberg, 1999; Demmel *et al*., 2014; Nir, 1982; Shock *et al*., 2005). Yet, there is limited research done on the effects of irrigation methods on the management of RKN and *R. solanacearum* disease complex.

Vermicomposting is the digestion of organic materials by earthworms that produce casts. The casts are reported to improve soil fertility and productivity of crops with no pollution of the environment (Gabour, 2015; Yadav and Argaw, 2016) and increase beneficial soil microorganisms (Alemu *et al*., 2014; Chaoui *et al*., 2003; Guerrero, 2010; Talashilkar *et al*., 1999). It also reported to stimulate and diversify microbial biomass and to suppress soil-borne plant pathogens (Yadav, 2011) through induction of systemic acquired resistance in plants, direct toxicity of degradation

products, and an increase of natural nematode-antagonist micro-organisms on the compost substrate (Oka, 2010; Zhang *et al*., 2011). The vermicompost prepared with farm wastes and animal manures were also reported to be rich in nutrients (Atiyeh *et al*., 2002; Arancon *et al*., 2006; Yadav *et al*., 2015).

In Ethiopia, limited research has been conducted which has examined the effects of vermicompost on growth, quality, and yield of vegetablecrops such as garlic (Alemu *et al*., 2014; Kenea and Gedamu, 2019) and potato (Yadav *et al*., 2015). However, no research work has been performed on the effect of vermicompost for management of RKN and *R. solanacearum*, and on the performance of potato cultivars. Therefore, the present research aiming to determine the effect of drip, sprinkle, and furrow irrigation methods alone and in combination with vermicompost for managing *Meloidogyne incognita* (MI) and *R. Solanacearum* (RS) disease complex are required. Thus, the objective of the study was to evaluate the effect of irrigation methods, cultivars, vermicompost on development of *M. incognita* and *R. solanacearum* diseases complex.

Materials and Methods

Description of the study site

The experiment was conducted at the 'Raare' Research Station of Haramaya University (HU), at an altitude of 2022 m.a.s.l. HU is located at 9°41"N latitude and 42°03"E longitude. The soil type of the station is silt loam.The area has a bimodal rainfall distribution with a mean annual rainfall value of 760 mm (Tekalign, 2011).

Experimental materials

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

Treatments and experimental design

Irrigation methods (drip, furrow and sprinkler), vermicompost and cultivars were evaluated for their effect on MI and RS, separately and in combination. The total number of treatment combinations was 39 (i.e. the 3 irrigation methods × 13 cultivars × vermicompost) and were laid out in a split-split plot designwith three replications. The irrigation methods were considered as a main plot, cultivars as a sub-plot while the vermicompost was considered as a sub-sub plot.

Plot size measured 4.5 m × 3.6 m consisting of six rows that could accommodate twelve rows of plants at space 0.75 m between ridges and 0.30 m between plants, with spacing between plots and adjacent replication of 1 m and 1.5 m, respectively were prepared for planting of the potato cultivars through drip, sprinkler and furrow irrigation methods, separately during the dry season of 2019-2020. Medium size tubers weighing approximately 39 g were planted at a

Table 1: *List of the tested potato cultivars with code, year of release, breeder, and recommended altitude for production.*

Cultivar	Accession code	Year of release	Breeder/ maintainer	Recommended altitude range for production a.s.l
Chirro	AL-111	1998	Haramaya University	1700 - 2400
Gudenie	CIP-386423.13	2006	Hawassa ARC/EIAR	1600 - 2800
Mara Charre	CIP-389701.3	2005	Hawassa ARC	1700 - 2700
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
Araarsaa	KP-90138.12	2006	Sinana ARC	2400 - 3350
Belete	CIP-393371.58	2009	Holeta ARC	1600 - 2800
Bedassa	AL-114	2001	Haramaya University	1700 - 2400
Bubu	CIP-384321-3	2011	Haramaya University	1700 - 2000
Dagim	CIP-396004.337	2013	Adet ARC	1700 - 2700
Shonkolla	KP- 90134.5	2005	Hawassa ARC/EIAR	1700 - 2700
Zengena	CIP-380479.6	2001	Adet ARC	2000 - 2800

Source: *MoANR (2017). ARC/EIAR = Agricultural research center/ Ethiopian institute of agricultural research.a.s.l = above sea level.*

depth of 5 to 10 cm. Each plot was watered based on Soil Water Tension methods at the 20 cm depth using a Tensiometer. Accordingly, 30-50 centibars (cb) for drip, 50 - 60 cb for sprinkler, and 60 - 80 cb for furrow irrigation were applied (Shock *et al.*, 2006).

Vermicompost preparation and administration

The substrates used for vermicompost preparation were wheat straw, *Parthenium hysterophorus*, and cow dung collected from the HU farm field. The wheat straw and *Parthenium hysterophorus* were cut into 3 cm pieces and mixed with cow dung in a 1:1:1 ratio . The mixed substrates were left in cement tanks (vermibed) measuring 2m × 1m × 1m. Moisture was maintained at 60% by sprinkling water (Edwards, 1983). One hundred composting earthworm species *Eisenia foetida,* commonly known as redworm, were introduced into the tank. The vermibed was covered with wire mesh, to protect the worms from predators. Harvesting was done on the 60th day (Krishnamoorthy and Vajranabhaiah, 1986; Yadav and Argaw, 2016), and the worms were separated from the vermicast. The casts were shade dried, passed through a 2 mm sieve (Pisa and Wuta, 2013), and applied in the soilat the rate of 4 t/ha during planting and before flowering (Arancon *et al.*, 2002).

Nematode extraction and identification

A soil sample measuring 1000 g was collected from each micro-plot before planting the cultivars. Soil and organic samples were also collected after 90 days of planting. The soil samples were collected using a sterile auger up to 25 cm soil depth. The organic samples of about 1000 g were collected using sterile scissors from the mother plants. The collected samples were bagged separately in polyethylene bags and labelled. The soil sample was sieved (2 mm mesh) to remove debris and gravel. After homogenization, sub-samples (100 g) were measured out for extraction. Nematodes were extracted using the Oostenbrink dish technique (Oostenbrink, 1960) then killed (at 65 °C) with hot TAF (7 ml formalin, 2 ml triethanolamine, and 91 ml distilled water) and mounted in fixative. From each micro-plot, about 25 specimens were examined under compound light microscopy.

Meloidogyne incognita was identified from other *Meloidogyne* spp. morphologically (head region) based on procedures developed by (Eisenback and Hirschmann, 1981). Soil samples collected from each micro-plot were also tested for the presence of *Meloidogyne incognita* with a bioassay test using susceptible '*Moneymaker*' tomato as an indicator plant. The tomato was grown in the collected soil samples in 500 cm^3 pots under greenhouse conditions. After eight-weeks, 5 g roots were collected from each pot, washed, and female nematodes stained with 1 ml acid fuchsin (3.5 g acid fuchsin/ 250 ml acetic acid and 750 ml distilled water) and then dislodged with a needle. The posterior portion of the female was cut with a knife and the body contents removed. The cleaned posterior portion of the female was trimmed and transferred to a drop of glycerine on a clean glass microscopic slide then subjected to observation under a stereomicroscope. *Meloidogyne incognita* was identified based on the perennial pattern described by Taylor and Sasser (1978). The results were also checked with *Meloidogyne* spp identified previously using molecular techniques.

Ralstonia solanacearum isolation and identification

A soil sample measuring 100 g was collected at a depth of up to 25 cm using a sterile auger from each micro-plot before planting the cultivars. The serial dilution method was applied for bacterial isolation. One gram of soil sub-sample was added to 9 ml of sterile distilled water. The soil suspension was shaken in a rotary shaker until homogenized and suspensions (1×10^{-4}CFU/ml) were poured in a Petridish containing TriphenylTetrazolium Chloride (TTC) solid media (Winstead and Kelman, 1952). The Petridishes were incubated at 28°C for 48 h. Bacterial colonies showing the irregular mucoid of RS were recorded and streaked on fresh TTC solid media for further purification. At 90 days after planting, RS present in the soil and organic materials were also isolated and identified to allow estimation of bacterial reproduction. RS isolateswere identified based on morphological, physiological, and biochemical tests (Goszczynska *et al.*, 2000).

Data collection

Final nematode population (*Pf*) was calculated by summation of eggsand soil population, reproduction factor (*Rf*) was calculated by dividing *Pf* by the initial nematode population (*Pi*). The number of galls per root systemand tuber (G/R), egg masses per root system and tuber (EM/R), root and tuber gall index (RGI), egg mass index (EMI) were recorded before planting (for *Pi*), and after ninety days of planting for the other parameters. The number of egg masses per root system and tuber were counted after

staining with phloxine 'B' (0.15 g/l water) according to Hooper *et al.* (2005). Root and tuber gall or egg mass indiceswere determined as described by Taylor and Sasser (1978). Resistance/susceptibility of the cultivars to the nematode was scored using ratings depicted by Pederson and Windham (1989). RGI = [∑ (Si × Ni) ÷ (N × 5)] ×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 and 5 > 100. Ni is the number of plants in each root and tuber galling scale. N is the total number of evaluated plants. Immune RGI = 0; highly resistant 0.1 ≤ RGI ≤ 5.0; resistant 5.1 ≤ RGI ≤ 25.0; moderately susceptible 25.1 ≤ RGI ≤ 50.0; susceptible 50.1 ≤ RGI ≤ 75.0; highly susceptible RGI > 75.0. Roots and tubers were rated for galling severity on 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 and tuber) according to Barker (1985).

The initial *R. solanacearum* colony number (RSI) was recorded before planting, while final RS colony number (RSF) was calculated by summation of RS in the soil and tuber after ninety days of planting. Appearance of symptoms and wilted foliage were also recorded. Resistance/susceptibility of the cultivars to bacterial wilt was scored using indices described by Winstead and Kelman (1952). Bacterial wilt index (BWI) = ∑ (ni × vi) ÷ (V × 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); and N=the number of plants observed. Highly resistant (BWI = 0.0 – 0.2), resistant (BWI = 0.21–0.3), 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 yield (MY), unmarketable yield (UMY), total tuber yield (TTY; MY plus UMY) in t/hawere recorded ninety days after planting.

Data analysis

All the *M. incognita, R. solanacearum*, plant related data, and their interactions were analyzed by one-way ANOVA following the procedures suggested by Gomez and Gomez (1984). The mean of the data werecompared using Duncan Multiple Range Test (DMRT) at $P \leq 0.05$. All analyses were computed using SAS software version 9.2 (SAS, 2009).

Results and Discussion

The development of Meloidogyne incognita on potato cultivars

The parameters of *Meloidogyne incognita* (MI): final nematode population (*Pf*), reproduction factor (*Rf*), number of galls per root systemand tuber (G/R), rootand tuber gall index (RGI), egg masses per root system and tuber (EM/R) and egg mass index (EMI) were highly significantly ($P \leq 5\%$) influenced by methods of irrigation, cultivars, vermicompost (VC), and their interactions (Supplementary Table 1).

Most of the tested cultivars showed different mean values of *Pf* with all tested irrigation methods. *'Gudenie', 'Belete'* and *'Bubu'* cultivars had the lowest *Pf* with drip irrigation amended with VC followed by sprinkler and furrow irrigation amended with VC whereas *'Jalenie'* had the highest *Pf* with all applied irrigation methods. '*Shonkolla'* also recorded the highest *Pf* with sprinkler and furrow irrigation methods in the soil which was not amended with VC. *'Gudenie'* had the lowestmean values (2.2) of *Rf* with drip irrigation amended with VC whereas *'Mara Charre'* had the highest mean values (8.6) of the parameter with sprinkler irrigation in the soil which was not amended with VC (Table 2).

None of the potato cultivars planted with different irrigation methods was free from MI infection. The cultivar *'Belete'* registered the lowest mean values of G/R (6.6) and RGI (2.0) with drip irrigation amended with VC, respectively while *'Jalenie'* registered the highest mean values of G/R (48.6) and RGI (4.0) with furrow irrigation alone, respectively. This cultivar also registered the second-highest value of the parameter with drip and sprinkler irrigation methodswithout VC. Egg masses were formed on all of the cultivars tested and with all applied treatments. The cultivar *'Belete'* generated the lowest mean values of EM/R (7.0) and EMI (2.0) with drip irrigation in soil amended with VC, respectively while *'Jalenie'* produced the highest values of EM/R with most treatments (Table 3).

All thecultivars planted under the differenttreatment schemes showed various galling scales and resistance categories to MI. The roots and tubers of all tested

Table 2: *Final nematode population and reproduction factor as influenced by irrigation methods, cultivars, and vermicopost.*

Cultivar	Irrigation methods											
	Final nematode population						Reproduction factor					
	D+VC	F+VC	S+VC	D	F	S	D+VC	F+VC	S+VC	D	F	S
Chirro	41.6bc	58bc	48c	67bc	82bc	70bc	3.4bc	6.1abc	3.9bcd	5.4abcd	7.8a	5.3bcd
Gudenie	26.6d	39.6f	31.6e	44e	56d	49.3e	2.2c	3.6cd	2.3d	3.1d	5.0c	4.3cd
Mara Charre	36c	56.3cd	44.3cd	61d	74.6c	65.6cd	2.9bc	6.3ab	3.1cd	7.9a	6.4abc	8.6a
Jalenie	50.6a	70.3a	59.3a	74.6a	93a	82a	4.8ab	5.9abc	5.1b	5bcd	7.9a	6bcd
Guassa	40bc	55.3cde	46cd	60.3d	78c	66.6cd	3.5abc	6.6a	3.4bcd	5.9abc	6.4abc	5.0cd
Gera	39.3bc	57.3cd	47c	62cd	77.3c	71.6b	3.7abc	6.1abc	3.3bcd	6abc	5.9abc	6.4bc
Araarsaa	39.6bc	53cde	48c	62cd	78.3c	70bc	5.7a	6.2abc	9.1a	5.9abc	5.3bc	4.8cd
Belete	24.6d	36.6f	29.3e	42.3e	54d	46e	2.4c	3.8bcd	2.8cd	3.6cd	5.8abc	3.8d
Bedassa	35.6c	51.3de	44.6cd	58d	73.3c	64.6d	3.2bc	5.4abc	3.8bcd	6.7ab	6.3abc	6.3bcd
Bubu	23.6d	37f	28.3e	41.6e	57d	47e	2.4c	2.8d	2.5d	3.4cd	6.0abc	4.5cd
Dagim	37c	49.6e	42.6d	58.3d	74c	63.6d	2.9bc	4.4abcd	4.1bcd	6.1abc	6.8abc	4.5cd
Shonkolla	44.6ab	63.3b	55.3b	69.6ab	89.6a	78.6a	4.0abc	5.1abcd	4.5bc	6.4ab	7.5ab	7.5b
Zengena	38bc	53.6cde	46cd	60.6d	74.3c	65cd	2.6bc	4.7abcd	3.9bcd	4.7bcd	5.0c	6.1bcd

Mean values sharing common letter(s) within columns of each parameter did not differ significantly at P ≤ 0.05 according to Duncan Multiple Range Test (DMRT). D+VC = drip irrigation amended with VC, F+VC= furrow irrigation amended with VC, S+VC = sprinkler irrigation amended with VC, D = drip, F = furrow S= sprinkler irrigation, VC= vermicompost.

Table 3: *Number of galls and egg mass per root system and tuber on potato cultivars as influenced by irrigation methods, cultivars, and vermicopost.*

Cultivar	Irrigation methods											
	Number of galls per root system and tuber						Egg mass per root system and tuber					
	D+VC	F+VC	S+VC	D	F	S	D+VC	F+VC	S+VC	D	F	S
Chirro	19.6ab	31ab	24.6ab	34.3ab	45ab	38.3abc	17.6ab	27abc	21abc	32.6a	40.3ab	33.6ab
Gudenie	9.0ef	16.6f	11.3de	19.3ef	26.3d	22.6f	8.6ef	14.6fg	10e	16.3ef	23de	19d
Mara Charre	11.3def	22e	15.6cd	25.3de	35c	29.3e	10def	20de	12.6de	22.6de	30.6c	24.6c
Jalenie	23.3a	34.6a	27.6a	38.0a	48.6a	42a	20.6a	31.6a	25.3a	33.3ab	43a	38.6a
Guassa	17.3abcd	27.3bcd	21.3abc	29.6bcd	38.3bc	34.3bcde	15abcd	24.6bcde	18.3bcd	26.6abcd	34bc	30.3bc
Gera	15bcde	28.3bc	21bc	29.6bcd	39.3bc	36.3abcd	13.3bcde	25bcd	18bcd	25.6bcd	34.6bc	32.3b
Araarsaa	23.3a	29.3bc	25.3ab	33.3abc	41.6abc	37abcd	19.6a	25.6bc	22ab	29.6abcd	37abc	33.6ab
Belete	6.6f	14.3f	9.0e	17.3f	24.3d	20.6f	7.0f	12.6g	8.3e	15.3f	22e	18.3d
Bedassa	15bcde	25.2cde	19.6bc	28bcd	36.6c	32.3de	12.6cdef	22.3cde	17.6bcd	25cd	33.3bc	29.3bc
Bubu	8.3e	14.0f	10ef	16.6f	24.3d	21.3f	8.6ef	12.6g	8.3e	14.6f	21.6e	18.6d
Dagim	18.3abc	25.6cde	21bc	29.3bcd	36.3c	32.6cde	16abc	22.3cde	18.3bcd	25.6bcd	32c	29.3bc
Shonkolla	20.6ab	32ab	25.3ab	34.6ab	45.3ab	38.6ab	18ab	29ab	22.3ab	30.3abc	40.6ab	35.3ab
Zengena	12.3cdef	22.6de	18c	26cde	34c	29.3e	11.6cdef	19.3ef	15.6cd	23.3cd	29.6cd	25.6c

Mean values sharing common letter(s) within columns of each parameter did not differ significantly at P ≤ 0.05according to Duncan Multiple Range Test (DMRT). D+VC = drip irrigation amended with VC, F+VC = furrow irrigation amended with VC, S+VC = sprinkler irrigation amended with VC, D = drip, F = furrow, S = sprinkler irrigation, VC = vermicompost.

cultivars showed light galling (LG) with drip irrigation amended with VC. *'Belete'* and *'Bubu'* generated LG with all tested treatments whilst *'Jalenie'*, *'Araarsaa'* and *'Shonkolla'* in all tested treatments produced moderate galling (MG) except with drip irrigation amended with VC which showed LG.

All cultivars that were grown with drip irrigation amended with VC fell under the'resistant' (R) category to MI. *'Gudenie'*, *'Belete'* and *'Bubu'* with all tested

treatments identified as 'R' while *'Jalenie', 'Araarsaa'* and *'Shonkolla'* with all tested treatment grouped under 'moderately susceptible (MS) except with drip irrigation amended with VC which exhibited 'R' (Table 4).

Development of Ralstonia solanacearum on potato cultivars

Ralstonia solanacearum related parameters: RS final colonies (RSF) and bacterial wilt index (BWI) were significantly influenced ($P \leq 0.05$) by methods of irrigation, cultivars, VC, and their interactions (Supplementary Table 2).

The lowest mean values of the RSF and BWI were registered for plants with drip irrigation amended with VC. However, plants with furrow, sprinkler, and drip irrigation methods without VC recorded the first, second and third, respectively highest values of the bacterial parameters. *'Belete'* recorded the lowest mean values (2.6) of RSF with drip irrigation amended with VC while *'Jalenie'* and *'Shonkolla'* recorded the highest values (8.6) and (8.5), respectively of the RSF with furrow irrigation alone. The mean values of initial RS colonies on which treatments were applied were found to be 2.9×10^5 (detailed data not presented). *'Gudenie', 'Belete', 'Dagim'* and *'Bubu'* registered the lowestmean values of BWI with the drip irrigation amended with VC. Among the tested cultivars, *'Jalenie'* registered the highest BWI with all tested treatments (Table 5).

Table 4: *Nematode resistance category on potato cultivars as influenced by irrigation methods and potato cultivars in soil amended with and without vermicompost.*

	Resistance category					
	Irrigation methods					
Cultivar	D+VC	F+VC	S+VC	D	F	S
Chirro	R	MS	R	MS	MS	MS
Gudenie	R	R	R	R	MS	R
Mara Charre	R	R	R	MS	MS	MS
Jalenie	R	MS	MS	MS	MS	MS
Guassa	R	MS	R	MS	MS	MS
Gera	R	MS	R	MS	MS	MS
Araarsaa	R	MS	MS	MS	MS	MS
Belete	R	R	R	R	R	R
Bedassa	R	MS	R	MS	MS	MS
Bubu	R	R	R	R	R	R
Dagim	R	MS	R	MS	MS	MS
Shonkolla	R	MS	MS	MS	MS	MS
Zengena	R	R	R	MS	MS	MS

R=Resistant, MS= moderately susceptible. D+VC = drip irrigation amended with VC, F+VC = furrow irrigation amended with VC, S+VC = sprinkler irrigation amended with VC, D = drip, F = furrow, S = sprinkler irrigation, VC = vermicompost.

Table 5: *Final Ralstonia solanacearum colonies (× 10^5) and bacterial wilt index as influenced by irrigation methods, cultivars, and vermicopost.*

Cultivar	Irrigation methods											
	***Ralstonia solanacearum* final colonies**						**Bacterial wilt index**					
	D+VC	**F+VC**	**S+VC**	**D**	**F**	**S**	**D+VC**	**F+VC**	**S+VC**	**D**	**F**	**S**
Chirro	4.4abc	6.3ab	5.3a	7.3a	8.3abc	7.5ab	0.17bc	0.44bc	0.28b	0.48b	0.76b	0.58bc
Gudenie	3.2ef	4.2ef	3.3c	4.4ef	5.8efg	5.1d	0.03e	0.11f	0.04g	0.30f	0.36c	0.33ef
Mara Charre	3.4cdef	4.6cde	3.9bc	5.5cde	6.4def	5.6cd	0.06de	0.29cde	0.14def	0.28cd	0.66b	0.33ef
Jalenie	4.4abc	6.7a	5.4a	7.1ab	8.6a	7.8a	0.30a	0.75a	0.37a	0.70a	1.0f	0.84a
Guassa	3.7bcde	5.6abcd	3.7bc	5.9bcd	7.3bcd	6.6abc	0.09cde	0.32bcd	0.18cde	0.29cd	0.71b	0.48cde
Gera	3.6bcde	5.7abc	4.6ab	5.9bcd	7.6abcd	7.0ab	0.11cde	0.35bcd	0.23bcd	0.32c	0.73b	0.55bcd
Araarsaa	4.8a	5.8abc	5.3a	6.7abc	8.0abc	7.4ab	0.23ab	0.46b	0.30ab	0.47b	0.84ab	0.70ab
Belete	2.6f	3.4f	2.9c	3.8f	5.3fg	4.6d	0.04e	0.14ef	0.05g	0.12ef	0.29c	0.40f
Bedassa	3.4cdef	5.2bcde	4.6ab	5.9bcd	7.3bcd	6.6abc	0.10cde	0.31bcd	0.23bcd	0.31c	0.71b	0.45cde
Bubu	2.9ef	3.4f	3.0c	3.9f	5.1g	4.5d	0.04e	0.11f	0.06fg	0.22def	0.35c	0.32f
Dagim	4.2abcd	5.3bcd	4.5ab	5.9bcd	7.0cde	6.4bc	0.04e	0.27de	0.11efg	0.31cde	0.63b	0.34def
Shonkolla	4.6ab	6.4ab	5.3a	6.7abc	8.5a	7.4ab	0.15bcd	0.36bcd	0.24bc	0.34bc	0.83ab	0.58bc
Zengena	3.0ef	4.5def	3.7bc	5.1de	6.4def	5.7cd	0.07cde	0.29cde	0.22bcd	0.32c	0.60b	0.35def

Mean values sharing common letter(s) within columns and rows of each parameter did not differ significantly at P ≤ 0.05according to Duncan Multiple Range Test (DMRT). D+VC = drip irrigation amended with VC, F+VC = furrow irrigation amended with VC, S+VC = sprinkler irrigation amended with VC, D = drip, F = furrow, S = sprinkler irrigation, VC = vermicompost.

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All cultivars except *'Jalenie'* and *'Araarsaa'*were identified as 'highly resistant' to RS with the drip irrigation amended with VC. The cultivars were also identified as 'highly susceptible'with furrow irrigation alone except '*Gudenie', 'Belete'* and *'Bubu'* which ranked as 'moderately susceptible' under the same treatment (Table 6).

The effect of irrigation methods, cultivars and vermicompost on yield of potato

All potato yield related parameters including marketable yield (MY), unmarketable yield (UMY) and total tuber yield (TTY) were highly significantly ($P \leq 0.05$) influenced by methods of irrigation, cultivars, and their interactions (Supplementary Table 3).

Guassa and *Bubu* had the highest mean values (47) and (47.9), respectively of MY with drip irrigation amended with VC. However,*'Bedassa'* and *'Dagim'* produced the lowest values (9.9) and (9.7), respectively of the parameterwith furrow irrigation without VC. *'MaraCharre'* and *'Zengena'* produced the highest mean values (18.1) and (17.5), respectively of UMY with drip irrigation amended with VCwhereas *'Bedassa'* and *'Dagim'* registered the lowest mean value (6.3) of the parameter with furrow irrigation alone. All the tested potato cultivars registered significantly different total tuber yield (MY plus UMY). *'Gudenie', 'Guassa', 'Belete'* and *'Bubu'* had the highest mean values (58.6), (59.6), (57.6) and (59.8), respectively of TTY with drip irrigation amended with VC nevertheless *'Gera', 'Bedassa'* and *'Dagim'* produced the lowest values (17.4), (15.4) and (15.1), respectively of the parameter with furrow irrigation without VC (Table 7).

Table 6: *Bacterial wilt resistant category of potato cultivars as influenced by irrigation methods, cultivars, and vermicopost.*

Cultivar	Bacterial wilt resistant category					
	Irrigation methods					
	D+VC	F+VC	S+VC	D	F	S
Chirro	HR	R	R	MS	HS	S
Gudenie	HR	HR	HR	R	MR	MR
Mara Charre	HR	R	HR	R	HS	MR
Jalenie	R	MS	MR	HS	HS	HS
Guassa	HR	MR	HR	R	HS	MS
Gera	HR	MR	R	MR	HS	S
Araarsaa	R	MS	R	MS	HS	HS
Belete	HR	HR	HR	HR	MR	R
Bedassa	HR	MR	R	MR	HS	MS
Bubu	HR	HR	HR	R	MR	MR
Dagim	HR	R	HR	MR	HS	MR
Shonkolla	HR	MR	R	MR	HS	S
Zengena	HR	R	R	MR	S	MR

D+VC = drip irrigation amended with VC, F+VC = furrow irrigation amended with VC, S+VC = sprinkler irrigation amended with VC, HR/S = highly resistant/susceptible, MS/R = moderately susceptible/resistant, R = resistant, S = susceptible.

Table 7: *The marketable and unmarketable yield of potato cultivars as influenced by irrigation methods, cultivars, and vermicopost.*

Cultivars	Irrigation methods											
	Marketable yield (t/ha)						Unmarketable yield (t/ha)					
	D+VC	F+VC	S+VC	D	F	S	D+VC	F+VC	S+VC	D	F	S
Chirro	39.8abcd	33.1d	35bc	28.2c	20.8c	26.3c	12.4bc	7.0de	6.3f	6.6cde	8.1bc	5.3g
Gudenie	44.6ab	38b	41.3a	32.8b	27ab	30.5b	13.7b	13.4a	12.1ab	11.7ab	12.3ab	10b
Mara Charre	36.2bcd	27.8f	30.7cd	23.5d	16.6d	21.3e	18.1a	7.6cde	7.3e	7.1cde	7.6bc	5.8f
Jalenie	34.5cd	32.6d	35.7bc	27.9c	21c	25.7c	14.5b	8.9bcd	8.5d	8.4cd	7.7bc	7e
Guassa	47a	41.6a	41.9a	36.3a	28a	33.5a	16.9ab	11.6ab	11.4b	12.7a	9.8abc	9.3c
Gera	30.6d	16.6k	18.9e	13.3h	10.5f	11.6i	12.1bc	7.2de	7.4e	6de	7.7bc	5.2g
Araarsaa	38.3abcd	20.4h	22.8e	16.5f	11.7f	15.2g	14.4b	8.8bcd	8.4d	8.2cde	7.9bc	6.8e
Belete	44.2abc	28.9e	31.8cd	24.4d	17.3d	22.3d	13.8ab	10.3bc	10.2c	9.6bc	9.6abc	8.1d
Bedassa	38.3abcd	18.7i	21e	14.9fg	9.9f	13.7h	12.7b	5.6e	5.1g	5.2e	6.3c	4.1h
Bubu	47.9a	37c	40.2ab	31.8b	23.6bc	29.7b	16.2ab	13.2a	12.8a	12.5a	13.2a	10.7a
Dagim	32.2d	18.4i	20.6e	14.6gh	9.7f	13.4h	10.7d	5.5e	5g	5.1e	6.3c	4h
Shonkolla	36.9bcd	26.3g	29d	21.9e	16de	20.2f	15ab	8.8bcd	8.4d	8.2cde	7.5bc	6.8e
Zengena	33.6d	17.7j	19.9e	14.3gh	12.5ef	13h	17.5a	8.4cd	7.3e	7.2cde	7.7bc	5.9f

Mean values sharing common letter(s) within columns of each parameter did not differ significantly at P ≤ 0.05 according to duncan multiple range test (DMRT). D+VC = drip irrigation amended with VC, F+VC = furrow irrigation amended with VC, S+VC = sprinkler irrigation amended with VC, D = drip, F = furrow, S = sprinkler irrigation, VC = vermicompost.

The development of *M. incognita* and infection of *R. solanacearum* were significantly influenced by methods of irrigation regardless of potato cultivars and vermicompost. In addition, the irrigation methods, the potato cultivars, and the use of VC affected both MI and RS. Plants grown with drip irrigation in soil amended with VC demonstrated the lowest mean values of G/R, EM/R, *Pf*, RSF and BWI compared with plants grown with sprinkler and furrow irrigation methods. Thus, use of the drip irrigation method, particularly in soil supplemented with VC may offer great potential for managing the MI and RS disease complex. Our data are in agreement with previous studies (Dasberg, 1999; Nir, 1982; Shock *et al*., 2005) which reported that drip irrigation reduces the transmission of pathogens while sprinkler and furrow irrigated soilis more suited for the dissemination of the pathogens. In terms of application of VC, the results presented here are consistent with those of earlier studies (Awad-Allah and Khalil, 2019; Akhtar and Malik, 2000; Edwards *et al*., 2007; Mohamed *et al*., 2019; Olabiyi and Oladeji, 2014; Pathma and Sakthivel, 2012; Yadav, 2011). These studies, conducted on different crops, reported VC application, suppressed nematode population increase, root and tuber galling and egg mass number found in the soil.

None of the potato cultivarswas found to be fully resistant to MI under any of the applied methods of irrigation. However, the potato cultivars reaction to MI were different. '*Gudenie*', '*Belete*' and '*Bubu*' were recorded as 'resistant' under all tested treatments while '*Jalenie*', '*Araarsaa*' and '*Shonkolla*' grouped under the 'moderately susceptible' category to MI except when grown by drip irrigation in combination with VC amended soil which allowed suppression of nematode reproduction to a level that allowed them to be considered 'resistant'. This implies that the presence of VC suppresses the development of MI. VC suppresses soil-borne plant pathogens through induction of systemic acquired resistance in plants, direct toxicity of degradation products and an increase of natural nematode-antagonist micro-organisms on the compost substrate (Oka, 2010; Zhang *et al*., 2011). Genetic differences between the different potato cultivars meant that they responded differentlyto the tested irrigation methods in terms of their response to nematodes. Considerable differences among potato cultivars to nematode infection have been recorded, ranging from highly susceptible tohighly resistant to nematodes. The resistant cultivars are infected by fewer developed nematodes than relatively susceptible cultivars (Bekhiet *et al*., 2010; Dropkin and Nelson, 1960; Hussain *et al*., 2016; Montasser *et al*., 2019). All the potato cultivars that were grown underdrip irrigation in soil amended wth VC fall under the 'resistant' and 'highly resistant' category to MI and RS, respectively. This showed that when plants are grown with drip irrigation with VC has a significant role in controlling both nematodes and bacterial disease complex growth and reproduction.

The highest values for MY, and TTY were recorded with drip irrigation in soil amended with VCcompared to un-amended soil. This may show the irrigation method and the presence of VC contribute incrementally to the plant yield parameters. Previous researchers (Dasberg, 1999; Nir, 1982; Shock *et al*., 2005) also reported that drip irrigation increases the marketable yield of crops more than sprinkler and furrow irrigated soil. A significant increase in plant growth parameters of pakchoi and garlic grown on soil supplemented with VC were reported (Kenea and Gedamu, 2019; Ramnarain and Abdullah, 2018). This might be due to the ability of VC to supply nutrients in a readily accessible form and also increases nutrient uptake by the crop which inturn enhances plant growth. VC may also suppress plant pathogens, thus enhancing plant health and minimizing yield losses (Oka, 2010; Pathma and Sakthivel, 2012; Zhang *et al*., 2011). Mohamed *et al*. (2019) also reported that the application of VC increased the quality of fruits, and increasesthe marketable yield of olive oil fruits through suppression of soil-borne plant pathogens.

Conclusions and Recommendations

From the present study, it can be concluded that *M. incognita* and *R. solanacearum* are influenced by irrigation methods, cultivars, vermicompost, and their interactions. The application of drip irrigation particularly in soil amended with vermicompost had a major impact on the *M. incognita* and *R. solanacearum* disease complex. These treatments positively affected tuber yield. More efforts are required to integrate disease management for sustainable control of such soil-borne disease complexes and to improve crop yield.

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Novelty Statement

This research is novel. No one has conducted it before.

Author's Contribution

All authors contributed to this part of a Ph.D. dissertation of the first author. Material preparation, data collection and analysis were performed by Tasew Getu. The first draft of the manuscript was written by Tasew Getu and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and material
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.

Supplementary Material

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Conflict of interest
The authors have declared no conflict of interest.

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