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A review on challenges and prospects of potato (*Solanum tuberosum*) production systems in Rwanda

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ABSTRACT

Purpose: Potato (*Solanum tuberosum*) is an important food and cash crop globally, particularly in Rwanda whereby it is ranked fourth most grown food crops after banana, sweet potato and cassava. The purpose of this review study is to analyze and understand potato yield production systems in Rwanda and to find out related constraints. **Main findings:** After key informants and various research work, it was found that the low potato yield (with on average 11.6 t/ha compared to yield potential of 50.6 t/ha), pests and diseases are the main constraints for potato production in Rwanda. However, it was revealed that the later are highly related to an inadequate supply of good seed tubers. Indeed, it is was reported that the actual mini-tubers seed production systems can cover up to 30% of the national demand; and hence farmers recycle their own seeds or get them from informal sources. This situation is leading to persistent pests and diseases particularly potato bacterial wilt (PBW) and late blight disease hampering potato productivity. **Limitations:** Soil erosion exacerbated by land fragmentation and use of steep land, and poor fertilization practices both in quantity and quality are reportedly highlighted in this review as secondary bottlenecks for potato production in Rwanda. **Directions for future research:** Active involvement of the private sector in seed production in conjunction with aeroponic systems and integrated pest and disease management (IPDM) is the promising future research path and most effective approach to be adopted for sustainable potato production and food security in the country.

INTRODUCTION

In the country of thousand hills, also known as Rwanda, potato is very important food crop. In 2017, it came at the fourth most grown crops after banana (*Musa* Spp.), sweet potato (*Ipomoea batatas*) and cassava (*Manihot esculenta*). In total 846,184 tonnes were produced (Fig. 1) in the same year in Rwanda (FAOSTAT, 2017). Muhinyuza et al. (2012) reported that potato is the most important cash crop and most consumed food in Rwanda. Potato is not a native crop of Rwanda. Seburanga (2013) had classified it, as neo-immigrant as a result of its appearance occurred during the colonization era, from the end of nineteen century. This food crop gains importance in Rwanda in the middle of the twentieth century, and his production and consumption have been since then growing.

Nearly all household income sources are made from potato production. Annual, it was reported to equal to 621,750 Rwf (Rwandan Franc), which is equivalent to 731 USD. Potato production was found to generate in average 57% of gross income per year and per household. In fact, potato production has been increasing in recent years. Potato is also parts of six leading crops for Crop Intensification Program (CIP); which is a Rwandan government agriculture policy implemented since 2007. Naturally, potato grows well in the highland of Rwanda with an altitude of 1,800 m and above (Danial et al., 2016).

Potato production

Due to suitable climatic conditions and high altitude, 60% of potato production in Rwanda is mainly from the Northern part of the country. It is mostly from these following districts: Burera, Nyabihu, Musanze, and Rubavu (Ferrari et al., 2017). Rwanda is ranked the third largest potato producer in Sub-Sahara Africa and the second in East Africa after Kenya (Mugabo et al., 2018). The scarcity of high-quality potato seeds is the country main constraint in potato production. It is recurrently limiting productivity and profitability (Danial et al., 2016). For instance, low-quality seed and low soil health are restraining yield to 11.6 ton ha^{-1} (Ferrari et al., 2017). Potato crop production system in the country often consists of a small family plot where it is grown and intercropped with beans and/or maize. In the intercropping farming systems, the average potato yield per hectare is estimated to 10 tons and in some part of the country farmers produce twice a year, however, the yield can be maximized up to more than 20 ton ha^{-1} for progressive farmers (Danial et al., 2016). Thus, all those figures (11.6 ton ha^{-1} for countrywide average, 10 ton ha^{-1} in intercropped farming and 20 ton ha^{-1} for progressive farm) are still low compared to the country production potential. In fact, Quiroz et al. (2014) have generated potato potential yields by using simulations and crop growth models. They have also quantified yield gap (Yg) in some sub-Saharan African countries like Burundi, Democratic Republic of Congo, Ethiopia, Kenya, Uganda, Tanzania and also Rwanda. Regardless of different and chosen experimental sites in those countries, the potato genotypes and seasons, the average potential yields were 50.6 ton ha^{-1} and the overall yield gap (or the difference between the potential yield and the average farmers' yield) turned to be 42 ton ha^{-1}. Other listed limiting factors are namely the omnipresence of recalcitrant diseases, low crop management skills, poor soil fertility, and inadequacy of high yielding cultivars, lack of potato commodity storage facilities and inadequate distribution and marketing (Danial et al., 2016).

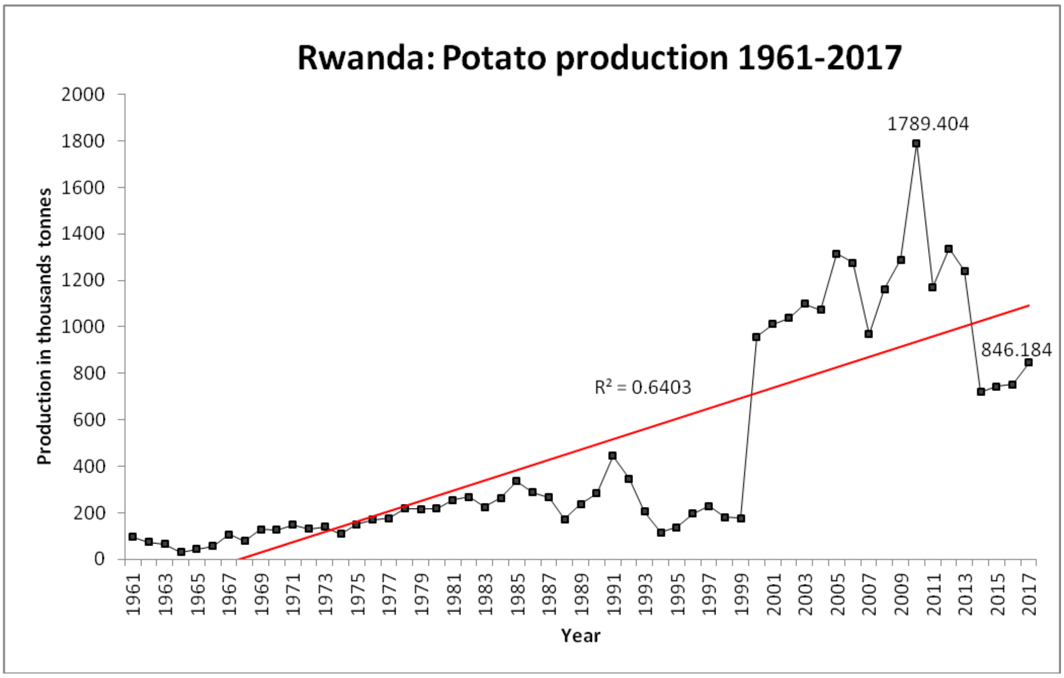

Fig. 1. Trends in the Rwanda potato production from 1961-2017 (Source: FAOSTAT, 2017).

The country's altitude on average is about 1,250 m. The lowest point is located in Rusizi valley at 950 m above sea level and the highest point is the mount Karisimbi pic at 4,519 m of altitude. As a result of this particular landscape, the temperature fluctuates in line with varying altitudes. Rwanda has a tempered climate due to its topography with four different seasons. There is a short rainy and short dry seasons and a long rainy and dry seasons. They are alternating from dry season to rainy season and so on. Potato (*Solanum tuberosum* Linn.) is a seasonal crop, and it is grown mainly during rainy seasons (Seburanga, 2013). There two main growing seasons in the country; season A which is running from the end of February and/or beginning of March up to early July and from September to early February for season B (FAO, 2016). In fact, by adding one off-season, they are counted as three growing seasons within Rwanda agricultural year. Firstly, season "A" intervene from September of one calendar year to February of the next calendar year. In that same next calendar year, season referred as "B" starts in March and ends in July. The last season referred as "C" or "off-season" starts in August and ends with September of the same calendar year (NISR, 2015). Potato has a short growing cycle which can take less than three to four months. Its production commonly follows two main growing seasons (February to May and September to December). Nevertheless, if there is enough soil moisture, the extension of the growing cycle is possible in some regions apart from the usual growing seasons (Danial et al., 2016). Modern irrigation systems, especially drip irrigation may allow potato production during the dry seasons in about all agro-ecological zones of the country.

Sole cropping of a single potato variety is generally preferred among farmers for potato production. Casually if large furrows or ditches are present, a row intercropping system is used in the production of potato where this crop is mixed with corn or beans or wheat. On the market, if the seed quantity is not fulfilled, unusually farmers have no other alternative than planting a mixture of potato varieties. Per household, it was found that nearly half of the land is used for potato production. Seasonally, in 77% of cases, farmers produce one potato variety (Ferrari et al., 2018).

Nonetheless, the demand for potato consumption has been on rising as the population has been increasing at a rate of 3%. Danial et al. (2016) citing Rwanda Agricultural Board's (RAB) report that in 2016 potato consumption was projected to reach 250 kg per capita and per year. Almost a 50% increase compared to 2008 where the consumption was 125 kg/year. By opposition, this figure is much higher in the sub-region. For instance, in Kenya and Ethiopia, the consumption per capita per year is 25 kg and 5 kg, receptively.

Cultivars

There are numerous potato varieties grown in Rwanda. Followings are grown in Musanze, Gicumbi, and Nyamagabe which are the top potato-producing districts in the country: Kirundo, Cruza, Mabondo, Victoria, Mabondo, Cruza, Kirundo, Kinigi, Rutuku, Kenya, Mugogo, Locale, Nyirangeli, Gasore, Makerere, Mizero, Nderera, Mbumbe, Rwishaki, kigega, IPP, Bineza, Nyabizi, Nyirabondo, Petero, Sangema, Gikungu, and Makoroni (Muhinyuza et al., 2012). Biniam et al. (2016) by assessing different potato (*Solanum tuberosum*) varieties from Eritrea, Kenya and Rwanda using molecular markers techniques, particularly using 12 highly polymorphic simple sequence repeat (SSR), they were able to measure genetic differences between closely related taxa. In their results, they noticed that both 12 studied Rwandan cultivars displayed a low genetic diversity. In fact, by Principal Coordinate Analysis (PCoA) most of the Rwandan cultivars were grouped together. They were cross related or too similar and displayed a low genetic diversity. Muhinyuza et al. (2012) have listed all preferred traits in potato cultivar by Rwandan potato farmers. They conducted a structured survey in three districts: Musanze, Gicumbi, and Nyamagabe. And it was found that farmers prefer disease tolerant cultivar particularly to late blight like Mabondo, Cruza, Kirundo, Kinigi, and Rutuku respectively from their tolerance level; from high tolerant to less tolerant. Other preferred attributes were; high yield and high dry matter content.

There are quite a few varieties that are actually under evaluation in the country. In the year 2016, RAB (RAB, 2017) reported that ten potato varieties originated from Netherlands (BRAMIN Ltd.) were being tested in National Performance Trial (NPT) in 3 selected sites: Cyuve, Cyanika, and Mudende. And in each site, they were compared with local varieties namely Kinigi and Kirundo. In the first season of trial, 2016-B (March-July) local varieties performed well in yield results than new varieties in Cyanika site. In Mudende site results were similar only for 3 imported varieties: HZD02, Panamera, and Voyager against Kinigi as local variety. In the third site, Cyuve result was very much alike both for new and local varieties. The following are other names of new tested varieties: Challenger, Derby, Fabula, Memphis, Sagitta, Sifra, and Taurus. In the same report by Rwanda Agriculture Board, it is stated that there is a joint effort with the International Potato Center (CIP) to improve local varieties through the crossing. The first trial had 98 potato clones (biofortified for iron and zinc) were being introduced and evaluated in 3 sites: Kinigi, Rwerere, and Sigira. The second trial had 16 bio-fortified clones in evaluation at these following sites: Kinigi and Rwerere. From obtained results, crossing block has been settled. Based on nutritional values, phenotypic features and yield, potential crossing potato parents were being assessed in order to generate new potato genotypes. Actually, this long period project (2014-2019) by CIP is also being carried out in other two East-African countries; Ethiopia and Kenya. More recently in 2018, fifty-seven biofortified clones with higher yields, better resilience to climatic stresses and which are late blight and virus diseases resistant were received in the region for multiplication and from them best clones will be further chosen by participatory variety selection. In the end, 5 to 10 clones will be assessed in different sites in Rwanda and Ethiopia and then released in the coming future guarantying farmer and consumer acceptance. The results of this considerable project are being expected in the first half of the year 2020 (CIP, 2019).

Nursery and propagation

Potato propagation is done in different ways; it is vegetative propagated via tubers and through sexual propagation. In this last method, botanical seeds are used and they are in most of the time referred to as true potato seed (TPS). Compared to seed tubers, TPS is much safer and does not host too many pathogens (Thomas-Sharma et al., 2016).

It was found by Ferrari et al. (2017) in their study conducted in four high potato producer districts (Burera, Nyabihu, Musanze, and Rubavu) that farmers were getting the big parts of potato seed from an informal origin. Thus its proportion equals 95% of seed demand. Predominantly from the farmer own harvest, other farmers and the local markets. The remaining 5% is being provided from a formal origin. Certified seeds on the market are still high in price and they are not enough in the country. There is a blatant dependency on uncertified potato seeds. The largest number of in vitro plantlets is produced and guaranteed by Rwanda Agriculture Board's laboratory (RAB) located in Musanze and also by the tissue culture laboratory of the Ruhengeri Institute of Higher Education (INES). Mostly mini-tubers are produced in screenhouses by using these two following methods: the aeroponic system and production on solid media with a single harvest. Per year, it exists two production cycles in each system (Ferrari et al., 2018).

Ferrari et al. (2018) have noticed that private entrepreneurs are using exclusively the one producing mini-tubers on solid media. Soon after screenhouse production, an open field multiplication follows. And two different categories of seeds are produced; "basic seed 1" and "basic seed 2". Further production phases (certification I and II) follows and it is exclusively done by cooperatives and by the "Groupes de Producteurs des Semences" (GPS). Certification II is only performed only in few cases.

Socio economic merit of potato

It was reported by Muhinyuza et al. (2012) that on average, the allocated land for potato production is about 1 hectare (ha) per household in the highland region where most of the potatoes are grown. Potatoes are taking a big part of the land than other food crops. For a total area equal to 2090 m^2, the highland region where most of the potatoes are produced is highly densely populated. It was found to have 670 people per square meter (m^2) for a total population of 1,137,900 (Ferrari et al., 2017).

Production constraints

Impact of climate change on potato production in Rwanda

Rwanda is affected by climate change. Indeed, many models predicted annual precipitation ranging from - 100 mm to + 400 mm in Rwanda between 2000 and 2050 (REMA, 2011b). The rainy season is expected to be shorter with heavy rains and also with a reduction of rainy days meanwhile dry seasons should be longer. Frequent rainfall deficits are expected in the eastern and southern provinces while increased rainfall is expected in the western, northern and part of southern provinces of the country (Warner et al., 2015). Yet, the severe drought of 2000 and the floods of 1997, 2006, 2007, 2008 and 2009 confirmed the above forecasts and annunciated the extreme climatic events Rwanda is called to face upcoming decades.

Besides, the average temperature has increased up to 2.0 ºC between 1970 and 2009 (REMA, 2011a). It is predicted to rise by 1 to 2.5 ºC between 2000 and 2050 and, 1 to 6 ºC by the end of the century (Mitchell, 2003; Ngoga et al., 2013). This is not without impact on the evapotranspiration of grown crops. Screening and extension of heat-tolerant potato cultivars in tropical and subtropical regions and, changes in the planting period, the use of later-maturing cultivars, and a shift of the location of potato production at high latitudes should be the best responses to global warming effect (Hijmans, 2003).

Furthermore, Rwanda's greenhouse gas (CO_2, CH_4, and N_2O) emissions had increased from 2,896.34 Gg to 5,793.45 Gg respectively in 2003 and 2006 (Byamukama et al., 2009). This increase is projected to reach 50% by 2020 (Mitchell, 2003). Nevertheless, there is no reason to worry. Under laboratory conditions, the increased CO_2 concentration has a positive effect on crop yields when examined as an isolated factor; this is particularly pronounced for potatoes and other tubers (Thomas, 2008). A potato tuber yield increased by 32% to 85% under high CO_2 concentration (Conn & Cochran, 2006; Craigon et al., 2002; Donnelly et al., 2001; Finnan et al., 2002; Heagle et al., 2003; Miglietta et al., 1998; Olivo et al., 2002; Schapendonk et al., 2000; Wheeler et al., 1991). The rate of this increase is estimated to be approximately 10% for every 100 ppm increase in CO_2 concentration (Miglietta et al., 1998) and the positive effects are chiefly attributed to the advancement of tuber initiation and flowering (Miglietta et al., 1998), reduction of transpiration rate by 16%, increase of instantaneous transpiration efficiency by 80% (Olivo et al., 2002), a photosynthesis increase from 10% to 40% (Katny et al., 2005; Olivo et al., 2002; Schapendonk et al., 2000; Vandermeiren et al., 2002) and tuber number increase (Craigon et al., 2002; Miglietta et al., 1998). Thus, climate change is expected to increase potato production in Rwanda by 25 to 90% between 2010 and 2050 (Warner et al., 2015). This figure was confirmed by Raymundo et al. (2018) who showed through the RCP8.5 (Representative Concentration Pathway) projection for 2055 that, the climate change will positively impact the potato production in tropic and subtropical regions such as Indo-Gangetic Plain, the highlands of South America, Asia, and Africa.

Soil degradation

There is real adversity about soil degradation and a blatant loss of fertility throughout the time due to poor management practices by farmers. We can mention among others; the limited use of organic fertilizers and insufficient crop rotation in a given period of time (Danial et al., 2016). The decrease in soil fertility, soil loss and landslides in the highland region concede with intensive farming. They are also linked to the highland features which are mainly steep slopes (Kagabo et al., 2013; Nahayo et al., 2016). For years, in order to mitigate soil erosion slow-forming terraces have been broadly used (Kagabo et al., 2013). In the country, it is recommended to adopt progressive terracing where there is up 12% of slope (Pande et al., 2014). Terraces efficiency relies on the use of sole grass strips (*Pennisetum purpureum*) or grass strips as barriers on the top edge of banks. In this situation, soil loss is reduced by more than 43% compared to soil or slopes without terraces. Grass strips barricade soil movement and they provide an extended resilience over twenty years. Unfortunately, with a long period of time fertility gradient emerge within the terraced slope. The lower parts of the terraces display considerable yield of potato and maize. It also displays more organic carbon content and high phosphorus concentration than the upper part (Kagabo et al., 2013).

Pests and diseases

Potato is infected by pests and diseases. Their existence in some production areas is the leading factor in the loss of potato yields. The following are pests and diseases that are more hampering potato production in the country.

Pests

White grubs (*Phyllophaga spp*. and other Scarabaeidae), locally known as "Ibishorobwa", are economical important pests of vegetables in Rwanda (Nyamwasa et al., 2017). Members of the family Scarabaeidae white grubs are easily recognized by their distinctive, lamellate club antennae (Ritcher, 1958). A recent study showed the outbreak of different species of white grubs that reach the astronomical density of 60 grubs m^{-2} in some areas of Rwanda; causing heavy damage in various vegetable crops including potato. The two prominent species of white grubs in the country are Anomala as well as Hoplochelus (Nyamwasa et al., 2017). Kajuga et al. (2018) evaluated the use of entomopathogenic nematodes (EPNs) in the management or biological control of white grubs (Coleoptera: Scarabeidae) in Rwanda. They conducted two small-scale field trials in 2014 and 2015 and they have found in soil-based laboratory bioassays that two types of EPNs strain *Heterorhabditis bacteriophora* and *Steinernema carpocapsae* can infect Anomala graueri larvae (Coleoptera: Scarabeidae) induce mortality within 7 days from 18 to 22% compared to the control at 100 infective juveniles per larva. High mortality level was also observed at 1000 infective juveniles per larva with 34 to 58% both for *Heterorhabditis bacteriophora* and *Steinernema carpocapsae* strains. The obtained results in potato fields (field efficacy trial) within 30 days and 60 days show that *Steinernema carpocapsae* (RW14-M-C2b-1strain) can reduce 29 ± 33% and 96 ± 3% of white grubs at 1×10^9 infective juvenile per hectare. These results revealed that EPNs are very promising solutions in the future biological control of the pests. And they are key components in the IPDM tools in potato production despite existence and use of pesticides by local farmers. It was also noticed that pesticides are still heavily used by farmers as a handy solution. They are applying at least 8 treatments per season from 3 different chemicals (Danial et al., 2016).

Another important and severe pest in Rwanda is Potato tuber moths (PTM) which cause yield loss in potato production both in the field and in storage. It has high reproductive and owns the potential to adapt to daily and seasonal changes. It is resistible to a few insecticides. One of the extensive pests is *Phthorimaea operculella* and it is a caterpillar insect pest. When infected, tubers are directly damaged in the soil by larvae. The control of the pest is difficult and chemical insecticide sprays have undetermined results (Abewoy, 2018). In a household survey conducted by Okonya et al. (2019) in the northern highlands of Rwanda (in these following districts; Burera, Gakenke, Musanze, Ngororero, and Nyabihu), potato tuber moth (*Phthorimaea operculella*) was ranked in top severe pests limiting potato production. In fact, up to 70% of losses in potato stores are attributed to tuber infestation by *P. operculella*. Other listed potato pests by farmers were Leafminer fly (*Liriomyza huidobrensis*), Aphid (*Myzus persicae*), Cutworm (*Agrotis* spp.), Whitefly (*Bemisia tabaci*) and Ants (*Dorylis orantal*). Compared to those others pests, respondents attributed to PTM a perceived level of importance (Weighted Average Index) equal to 0.69 in a range varying from 0.0 (for not a problem) to 1.0 (for most important constraint). It was the highest and also the same level attributed to Aphids and Cutworms. Whitefly, Leafminer fly and Ants were following as less constraint.

Diseases

Potato is worldwide infected by bacteria, fungi and phloem limited pathogens including virus and virus-like agents. In the East-African region, several viruses have been reported to infect potato. These include Potato leaf roll virus (PLRV), Potato virus Y (PVY), Potato virus Y (PVX), and Potato virus A (PVA) which their presence where confirmed in major potato growing zones of Kenya (Gildemacher et al., 2009). Likewise, Kakuhenzire et al. (2000) corroborate the existence of PLRV and PVX in Uganda. Potato virus S (PVS), PVX, Potato virus M (PVM) PLRV, and PVY were found to be distributed in Ethiopia (Bekele et al., 2012). Unfortunately in Rwanda, such kinds of researches on potato viral diseases are lacking up to date. Thus, information on the identity and relative importance (distribution and status) of viruses is crucial for effective crop management. Considering that viruses and bacterial wilt incidence were recognized to be linked with the general lack of clean seed (Schulte-Geldermann, 2012). The high dependence of farmers on the informal source of seeds coupled with the use of vegetative propagated seeds and the mismanagement of pests in field is thought to play a critical role in the epidemiology of potato diseases. Here are the reported diseases on potato in Rwanda.

Late blight

Late blight disease is known to be caused by *Phytophthora infestans* (Muhinyuza et al., 2007; Razukas et al., 2008). When weather conditions are convenient for a long successive time in terms of high relative humidity, cool temperature, and soil moisture, the disease can be severe (Muhinyuza et al., 2007). Late blight is one of the most devastating diseases in many plants. Annually, there are multibillion-euro losses worldwide due to late blight mostly in potato and tomato production. The fungus firstly infects leaves, stems and later on the infection will spread in all plants (Razukas et al., 2008).

It was found by Njoroge et al. (2019) that in Rwanda there is dominance of a European lineage of the pathogen known as “2_A1” and also the perpetuation of an old “US-1” lineage in small proportion compared to how it used to be. Thus, it was confirmed that the old US-1 lineage is being displaced by 2_A1 in the East African region. The experiment conducted in Kinigi (Northern highlands) by Muhinyuza et al. (2007) on the susceptibility of eight potato cultivars (Cruza, Gikungu, Kigega, Kirundo, Mabondo, Mizero, Sangema, and Victoria) to *Phytophthora infestans* point out Victoria as the most susceptible cultivar, Gikungu the most resistant and Kigega, Cruza, and Mizero as tolerant. The comparison of two growing seasons (2005-B and 2006-A) for their weather features also revealed that 2005-B (March-July) season more favorable to the development of potato late blight. Indeed, the season 2005-B (March-July) was characterized by; 145.5 mm.month^{-1} of rainfall, 90% of relative humidity and temperature between 15-20 ^{o}C. These patterns influenced in significant development of potato late blight and therefore resulted in lower yield. During season 2006-A (September-February) conditions were slightly different; rainfall equaled 45.34 mm per month, relative humidity was below 75% and the temperature was between 14-21^{o}C. Consequently, these weather conditions were not in favor of late blight development and it less appeared.

Yield response (tuber yield, tuber weight, dry matter content, etc.) and late blight resistance have been evaluated under local environmental conditions to determine suitable parents for breeding between local and imported genotypes from CIP. Forty-four different genotypes were initially tested in this study in three different sites (Kinigi and Rwerere in the Northern Province and Nyamagabe in the Southern Province). Among them, thirty were acquired from CIP and fourteen were local varieties. Results show that eight genotypes were labeled as the most promising parents for future breeding studies. Gikungu, Ngunda, Kigega, and Ndera were promising local genotypes and from CIP’s genetic materials, there was; CIP 391047.34, CIP 393385.39, CIP 393280.84, and CIP 396036.201. The disease severity of the sites were found to be highest in Nyamagabe (29^{o}33' East, 1^{o}33' South) with 33%. Rwerere (29^{o}19' East, 1^{o}36' South) came second and Kinigi (29^{o}38' East, 1^{o}30' South) in last position with 30.9% and 20% respectively (Muhinyuza et al., 2015). Muhinyuza et al. (2016) performed crosses between eight complementary parents with the purpose of assessing the combining ability effects for tuber yield, yield related and late blight resistance traits in potato. Crosses were carried out in Kinigi and Nyamagabe sites. Results show that only four parents; Gikungu, Kigega, CIP 393036.201, and CIP 391047.34 were the best cross combinations to do for future potato release. Thus, the resulting ten families (parents and F_1s) had high tuber yield and resistance to late blight. The GCA (General combining ability) to SCA (specific combining ability) ratios was more or less equally essential in the expression of late blight resistance, tuber yield and yield related traits in potatoes.

Potato bacterial wilt (PBW)

Potato bacterial wilt (PBW) also call potato brown rot, is caused by *Ralstonia solanacearum*. It is among the main potato diseases in Rwanda (Mutimawurugo et al., 2019). PBW is a threat to potato production and his perseverance in the soil is obvious for a long period of time (Uwamahoro et al., 2018). Mutimawurugo et al. (2019) carried out in vitro identification and characterization study of pathogen isolates in bacterial wilt most vulnerable potato cultivars (Gikungu, Kinigi and Kirundo) grown in Rwanda. All the obtained isolates were confirmed by Biovar test to belong to race 1 biovar 3 of the pathogen and they were found to be pathogenic to potato plants. The pathogenicity test of those isolates on potatoes was also carried out by in vivo experiments under greenhouse conditions. The wilting rate caused by those bacterial isolates was measured every 5 days up to 20 days after inoculation. Calculation and evaluation of disease incidence (DI) and disease severity (DS) were also done in the same interval (5 days). Gikungu and Kinigi isolates were highly virulent than Kirundo isolates with disease severity (DS) scores of 100%, 97.33% and 94.67% in Gikungu isolates, Kinigi and Kirundo respectively. The disease incidence (DI) also comes in the same order with 100% observed in Gikungu isolates, 98.25% in Kinigi and 92.61% Kirundo.

In a field study conducted in 2015 in eight districts of Rwanda, PBW has been classified as the main and the most spread potato disease in Rwanda (Uwamahoro et al., 2018). The disease incidence and severity varied respectively from 5 to 24% and 3 to 13%. The incidence was higher in minor producing districts and lower in major producing districts. The same study revealed low awareness and knowledge regarding the PBW disease management among farmers. The disease is mostly disseminated through seed tubers as great numbers of farmers are so often using seeds tubers from their own fields. This extended use of seeds from contaminated soils exposes their entire field the epidemiology of the disease and in the end yield decrease year after year. The reduction of pathogen dissemination and attenuation loss in yield goes through the non-retaining of seed tubers by farmers from their own fields no more than two cycles. Another PBW management measure is potato rotation with cabbage, beans and/or carrot within one and/or two seasons (Kassa, 2017) while crop rotation, high altitude, intercropping is associated with low PBW incidence and severity (Uwamahoro et al., 2018).

Seed supply systems in the country

National strategies have been put in place in order to mitigate the shortage of certified tuber seeds on the market. The formal sector led by Rwanda Agriculture Board (RAB) with the assistance of a few private companies is putting tremendous effort in germplasm maintenance. Through in vitro tissue culture, clean seeds are being produced. And by using conventional and aeroponic methods mini-tubers are released. RAB (2017) reported some results figures in this matter for the year 2016-2017. Tissue culture method produced a total of 1,283,770 in vitro plantlets; 1,054,000 mini- tubers resulted from conventional greenhouses in soil medium; 8,002,166 mini tubers derived from direct transfer from laboratory to the field and 653,891 mini-tubers were produced through aeroponics.

Despite these promising numbers, national demand is far from being satisfied with potato tuber seeds. In order to reduce this gap, cheap, locally adaptable and reproducible methods to satisfy demand in seeds before each growing season are on trial. One of the solutions recommended by Danial et al. (2016) for the all East African countries is to introduce F1 hybrid potato due to his numerous benefits compared to the conventional potato breeding technology; for instance, it is possible to get hybrid potato adapted to local conditions and co-created by local stakeholders. And in one growing season, large quantities of disease-free true hybrid seeds are obtained. They can be also an exceptional starting material for further production. F1 hybrid potato cultivars may contribute to food security and considerably increase profitability and yield. The followings are some of the benefits offered by hybrid breeding technology; clean seeds, fast multiplication, easy storage, fast breeding, improved breeding, and dedicated breeding. Constantly in the new breeding program, the used and starting materials are local potato cultivars from farmers which provide in the end numerous adaptable varieties (Danial et al., 2016). From the new variety in germplasm, among clones that have been evaluated and selected from RAB-CIP trials, there are; CIP393077.159, CIP 392617.54 and CIP 393371.58 and they are more outperforming and promising clones with an average in yield above 20 ton ha^{-1}. They are actually maintained in vitro and in an open field for a breeding purpose (RAB, 2017).

Proposed solutions and future perspectives

The main factor for yield loss and also the major dissemination pathway of potato bacterial wilt is through informal sources of potato seeds always spinning between farmers year after year (Kassa, 2017). This continued propagation leads eventually to seed degeneration and yield loss due to a decrease in health status (Muthoni et al., 2013; Thomas-Sharma et al., 2016). Seed degeneration has been defined as “An increase in pest and/or pathogen incidence or severity, associated with a reduction in yield or quality of seed tubers over successive cycles of vegetative propagation” (Thomas-Sharma et al., 2016). The main cause of seed degeneration in potato is the accumulation of virus and viroid in tubers due to their vegetative propagation (Muthoni et al., 2013).

In the prospect of disease management, it was found that if a complete rotation of potato crops after one or two seasons with beans and cabbage reduced wilt incidence, latent infection in tubers and increased tuber yield. It was suggested that in areas where PBW occurs and persist, integrated control options such as crop rotation should be proposed. Thus, the impacts of crop rotation have been found to reduce significantly pathogens in the soil. Also, the number of latent infections has been reduced circumstantially in tubers which are the pathogen vectors and dissemination agents in the uninfected area (Kassa, 2017).

As part of the solution to reduce Seed-borne diseases of potato and also diseases spreading through the informal sector, the aeroponic production system was evaluated by RAB in two distinct studies as promising ways to produce mini-tuber seeds. Successful and future potential cultivars were identified. In fact, the rapid multiplication of potato seed can be achieved by this system. In an aeroponic production system, plant roots grow in the air and in the enclosed environment. A mist nebulizer is used to supply different nutrients into the enclosed growing system like; nitrogen (N), phosphorus (P), magnesium (Mg), calcium (Ca), and others. A fine mist of solution with nutrients is created and conveyed onto the roots (Khadka et al., 2018). Aeroponic is ten times more efficient in higher yields than the traditional methods (Otazu, 2010). Besides, the infection rates of soil-born diseases are kept at an extreme low level. The original plant materials generally come from in vitro potato plantlets (Khadka et al., 2018). The efficiency of an aeroponic system in reduction serious disease transmission in potato is well recognized and the system is also being tested in other Sub-region countries like; Ethiopia, Kenya, and Uganda (Tessema & Dagne, 2018). In 2013, a study was carried out by Masengesho et al. (2013). They only evaluated two commercial

Kinigi and Kigega. They have concluded that in terms of adaptability in the aeroponics environment, Kinigi variety was superior to Kigega. More recently, Khadka et al. (2018) assessed four commercial potato varieties namely CIP393371-58, Kigega, Kinigi and Kirundo. And according to different checked features such us; plant height and number of nodes; maturity period and number of produced mini-tuber per plant. It was found that CIP393371-58 was far superior to other cultivars and it was more adaptable in the aeroponic production system. It was followed in this study by Kinigi, Kirundo, and Kigega, respectively. Indeed, CIP393371-58 was mature only 70 days compared to the second variety Kinigi with a maturity period of 77 days and there was in average 41 mini-tubers per plant for CIP393371-58 compared to 36 mini-tubers obtained in Kinigi as second variety. In summary, the aeroponic production system is genotype-dependent and it is always associated with another mass propagation method like tissue culture.

The adoption of true potato seeds (TPS) screened for their resistance or tolerance to main virus, virus-like diseases and pests of potato is considered in the mitigation of diseases and pests' occurrence. All players in potato production, both formal and informal sector should adopt an integrated strategy for each disease and pests. Because there is no single effective strategy for a given disease or pest, they should maintain control and assessment during potato tuber seeds production and in the propagation phase. Farmers should maintain active screening of their crop during growth and they should avoid cross-contamination in their practices and cultivation routines.

CONCLUSION

Potato (*Solanum tuberosum*) is one of the major food and cash crop of the agricultural sector in Rwanda, whereby the economy of the country is heavily depending on agriculture. Over the last decade, research has made an attempt to address some of the prominent challenges in the sector, and there is a substantial improvement in the potato production systems. Nonetheless, there is along away to go to boost production and improve the quality of potato in Rwanda. Recent evidence has underlined the lack of certified seed and farmer's limited skills particularly in soil management and post-harvest technologies, as the major setbacks for potato production sector in Rwanda. The massive use of quality potato seed is largely impeded by non-timely-availability of potato certified seed and relatively high cost associated with certified seed production. The use of low-quality seed has been also reported as one of the key driving factors enhancing the disease outbreak, hence the disease treatment affecting potato production but also increasing its production cost. Besides, due to lack of storage skills and facilities, there is a big loss frequently observed and a fall or unpredictable fluctuation of potato market price hence affecting negatively potatoes growers' profit margin.

From the perspective of boosting potato production in Rwanda, the main efforts should be directed to encourage and support the private sector to venture into potato seed production particularly in the multiplication of good quality seed. Also, there is a need for continuous research on climatic resilient and diseases tolerant potatoes varieties but, also builds the farmers' knowledge and skills on good farming practices namely; the Integrated Pest and Disease Management (IPDM) techniques and post-harvest technology. Drawing to an end, it is also worth to mention that to improve farmers' livelihood in Rwanda, there is a high need to organize and connect farmers to better and profitable markets and avoid in between third parties like brokers in the commercialization chain without relevant addition values.

Conflict of Interest

The authors have no conflict of interest to report.

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