Placide *et al. CABI Agriculture and Bioscience* (2022) 3:40
https://doi.org/10.1186/s43170-022-00105-7

CABI Agriculture and Bioscience

RESEARCH

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Yield performance, adaptability and processing qualities of pre-release potato clones under different Rwandan agro-ecologies

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Abstract

Five new potato clones (CIP393280.64, CIP393371.58, CIP393077.159, CIP396018.241, and CIP398190.615) and two local checks (Kinigi and Kirundo) were evaluated in fourteen sites under the National Performance Trials (NPTs) for two growing seasons using a randomized complete block design with three replications to identify their yield performance, adaptability and processing qualities. The data related to yield (number and weight of tubers per plot, marketable and unmarketable yields, and total yields) and processing qualities (tuber shape and depth of eyes, dry matter content, frying time, crisps color, taste, crunch, waste percentage, and conversion rate) were collected and analysed using GenStat 20th edition. The analysis of variance revealed significant effects of clone, site, and clone by site interaction on fresh tuber yield. Across all sites for both seasons, the clones CIP393077.159, CIP393371.58, and CIP393280.64 revealed the yields of 31, 28. and 27 tons/ha that fall in the same range of yields as local checks Kinigi and Kirundo with 30 and 35 tons/ha, respectively. Based on yield stability index (YSI) ranking combining high yield and stability, the first four genotypes were Kirundo, CIP393077.159, CIP39601.241, and CIP393371.58 with YSI of 16.6, 11.3, 9.1, and 7.3, respectively. All the new tested potato clones revealed higher dry matter (DM) content that was above 18% of total fresh weight except CIP396018.241 which had a DM content of 17% of fresh weight. This dry matter content was comparable with the dry matter content of local check Kinigi, the most popular varieties variety used for French fries in Rwanda. Based on crisps color, the clones CIP393077.159, CIP393280.64, CIP396018.241, CIP398190.615 showed the same trend as local check Kinigi. The crisps from these clones were ranked as good or very good for taste and crunch. The results of this study highlighted that the clones CIP393371.58 and CIP393077.159 can be recommended as candidate for new varieties for high fresh tuber yields; while the clones CIP398190.615, CIP396018.241, and CIP393280.64 can be recommended as candidate for new potato varieties for crisps and French fries.

Keywords: National Performance Trials, New potato clones, Processing traits, Seasons, Yield performance

Introduction

Potato (*Solanum tuberosum*) is the fourth among the worldwide food crops after maize, wheat, and rice, with annual production of 370.4 million metric tons harvested on 17.3 million hectares of land, with a productivity of 20.9 tons/ha (FAOSTAT 2019). Among roots and tuber crops, potato is the first in terms of volume produced and consumed followed by cassava, sweetpotato, yams and taro. Potato is grown in more than 150 countries, under temperate, subtropical and tropical conditions, and constitutes a staple food of about one billion people in the world in which about a half is localized in the developing counties (FAOSTAT 2019). According to the total

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worldwide potato production statistics, about of 54% of the production is coming from China, India, Russian, Ukraine, and United States of America. The Rwanda is ranked 46th and 9th in terms of production worldwide and in Africa, respectively (FAOSTAT 2019).

Potato provides more nutritious food per unit of land and time and under hostile conditions compared to other food crops. It is one of the most efficient crops in converting natural resources into a high quality food, with high yields and with good response to agriculture inputs (Horton 1987). Potato is consumed in different forms such as boiled, roasted, French fries, chipped and others, and constitutes an important source of food for many low-income people in both urban and rural areas (Kibar 2012). Potatoes are very rich in various nutrients such as carbohydrate, amino acid, vitamins, minerals, antioxidant, dietary fibers, and protein (Beals 2019; Burgos et al. 2020). The protein of potato was reported to be very rich in lysine and low in sulphur holding amino acids and potatoes are nearly free of fat and cholesterol as opposed to other staple food (Bártová et al. 2015; Kowalczewski et al. 2019). The nutrition quality of potato make it a health staple food. Potato tubers provide raw materials to industries producing chips, crisps, starch, spirits and alcohol (Das et al. 2021). This high value and importance of potato were the reason of its high adoption by farmers and dissemination by governmental agriculture agencies.

In Rwanda, potato is an important crop grown for family food security and income generation. It is now being cultivated throughout the country, particularly in Birunga, Buberuka and Congo Nil Watershed Divide agro-ecological zones, where rainfall and soil conditions are favourable. Potato covers 4% of total cultivated land per each growing season, but it provides 10% of total main crop production in Rwanda (NISR 2019). Most of potato producing sectors consists of small family farms that intercrop potato with beans and maize, and yield average is still low (around 10 tons/ha) compared to other countries such as The Netherlands and German that can reach up to 35 tons/ha (FAOSTAT 2019). The main challenges causing this low potato productivity include small and fragmented potato production land, poor linkage of potato producers and markets, limited access to credit for agriculture inputs, shortage of appropriate post-harvest handling and processing technologies, inadequate supply of high quality seeds to farmers, low rate of fertilizer use and irrigation, pest and disease problems, and limited number of improved and high yielding potato varieties adapted to current biotic and abiotic stresses worsened by the current climate changes (Muhinyuza et al. 2012; Rukundo et al. 2019).

Most of current popular potato varieties grown in Rwanda were developed before 1994 genocide that destroyed most of the country research capacity including human resources and infrastructures (Rukundo 2019). These varieties were developed based on the needs of that time; nowadays, the needs have changed. With the current development of potato processing industries, it is required to develop potato varieties with specific characteristics such as high dry matter content, low reducing sugar content, good shape, and shallow eyes (USAID 2016). In addition to change in needs, the current climate changes brought new biotic and abiotic stresses (Mori et al. 2015). The sustainability of potato production will depend on availing new adapted varieties resistant or tolerant to the current and new coming production constraints, and meeting preferences of the end-users. In the attempting to develop new potato varieties that meet the current needs, the Potato Sub-Program of Rwanda Agriculture and Animal Resources Development board (RAB) in collaboration with the International Potato Center (CIP), has selected 5 potential clones as candidates for new potato varieties to be released in Rwanda. The present study was aimed at identifying their yield performance and adaptability under different agro-ecological zones in Rwanda, and their processing qualities.

Materials and methods

Planting materials

The potato planting materials tested in this study were five new potato clones namely CIP393280.64, CIP393371.58, CIP393077.159, CIP396018.241, and CIP398190.615, and two local potato varieties (Kinigi and Kirundo). The description of these planting materials is detailed in Table 1.

Sites of trials

Trials were carried out in two growing seasons; season 2018B and 2019A. The season B starts from February to June, while season A starts from August to December. In both seasons, trials were established in 15 sites located in four agro-ecological zones, among them 3 zones namely Virunga, Buberuka and Congo Nile Divide being important potato producing areas in Rwanda (NISR 2019). Trials were established at Kisaro and Ruhunde sites of Buberuka Highland agro-ecological zone, Cyuve, Kabatwa, Jenda and Busasamana sites of Virunga agro-ecological zone, Karongi, Mukura, Nyabirasi, Uwinkingi, Nyabimata and Kigeme of Congo Nile watershed divine agro-ecological zone, Kayonza and Rwamagana sites of Eastern savanna agro-ecological zone, and Muko site of Central platau agro-ecological zone.

Trial establishment

The trials were established using a randomized complete block design with three replications. All genotypes

Table 1 Description of tested potato planting materials

No	CIP ID	Given local name	Processing potential	Disease resistance or tolerance*
1	CIP 393280.64	Nkunganire	Chipping and French fries	Late blight resistant and bacterial wilt tolerant
2	CIP 393371.58	Twihaze	French fries	Late blight resistant
3	CIP 393077.159	Kazeneza	Chipping and French fries	Late blight resistant and bacterial wilt tolerant
4	CIP 396018.241	Izihirwe	Chipping and French fries	Late blight resistant
5	CIP 398190.615	Ndeze	Chipping	Late blight resistant and Heat tolerant
6	Local variety 1	Kinigi	Chipping, French fries and fresh consumption	Tolerant to late blight
7	Local variety 2	Kirundo	Chipping, French fries and fresh consumption	Tolerant to late blight, susceptible to bacterial wilt

* https://research.cip.cgiar.org/cipcatlg_ac/Catalogue.php?cipnumber=CIP391002.6

were planted in four row plots of 10 tubers per row giving a total of 40 plants per plot with inter-row spacing of 80 cm and intra-row spacing of 30 cm. The experimental plots were surrounded by two border rows planted with Kirundo variety. Organic manure (chicken manure from the same farm) was applied at planting at a rate of 20,000 kg/ha and mineral fertilizer ($N_{17}P_{17}K_{17}$) was applied at a rate of 300 kg/ha. The total amount of organic fertiliser was applied during planting, while half (150 kg/ha) of mineral fertilizer was applied during planting, and another half during hilling up. Weeding was carried out manually when it was needed. The control of pests such as Aphids and Potato leaf miners was controlled by spraying using alternate products which have the active ingredients of Abamectin 18 g/L, and Profenofos 40% + Cypermethrin 4% EC. Late blight disease was controlled by spraying Ridomil, a systemic fungicide applied at 30 days after planting at about 95% crop emergence at a concentration of 50 g/15 L of water. This application of systemic fungicide was repeated two times with an interval of 7 days. After application of Ridomil, late blight disease was continuously controlled by spraying Dithane (Mancozeb), a contact fungicide at a dose of 50 g/15 L of water. Spraying was repeated every 7 days to ensure the control of late blight. The trial was dehaulmed at fully maturity, 120 days after planting. Harvesting was carried out at 135 days after planting and tuber samples for each variety were collected and sent to a processing company to assess their processing qualities.

Data collection

The data collection consisted of yield and processing data. The yield data included number and weight of tubers per plot, marketable and unmarketable yields, and total yields. To determine the marketable and unmarketable yields, tubers were sorted and classified into three groups: (1) tubers weighing 200–300 g or tubers with a diameter equal or bigger than 60 mm, (2) tubers weighing 80–200 g or tubers with a diameter ranging between 30 and 60 mm, and (3) tubers weighing less of 80 g or tubers with a diameter that is less than 30 mm (De Haan et al. 2014). The number and weight of tubers of each category and for each variety were determined. The category one and two were classified into marketable yield while the last category was classified as unmarketable yield.

Processing quality data consisted of identifying phenotypic characteristics of processing qualities such as tuber shape and depth of eyes using visual inspection at harvesting time. Other processing qualities such as dry matter content, frying time, crisps color, taste, crunch, waste percentage, and conversion rate were tested by Hollanda FairFoods (WINNAZ); a private potato processing plant based in Musanze district, Northern province of Rwanda. The dry matter content was determined using underwater weight method as detailed by Haase (2003). Potato samples were put in bags, and the weight in air was determined and recorded using precise balance. Eighty litters of water were filled in an open tank and the weighed potato sample was dropped until at the bottom of the tank. The bag of samples was kept suspended in the water and the weight was determined. After recording the weight in air and in water, the specific gravity and dry matter content were determined using the following formula:

$$Sp.gr = \left[weigh\ in\ air/\left(weigh\ in\ air - weigh\ in\ water\right)\right], \quad (1)$$

$$Dry\ matter\ \% = \left[24.182 + 211.04\left(sp.gr - 1.0988\right)\right] \quad (2)$$

The sugar content was assessed using a standard color chart after frying according to CIP (2007).

Data analysis

Data collected were processed by analysis of variance (ANOVA) using GenStat 20th edition (Payne et al. 2011). When the significant differences among genotypes, sites, and seasons were detected, the mean separation was performed with the Least Significant Difference (LSD) test (P = 0.01 and P = 0.05). The stability and adaptability of tested potato clones were determined with the Additive

Main Effects and Multiplicative Interaction (AMMI) statistical model (Gauch 2006) using also GenStat 20th edition (Payne et al. 2011). AMMI's stability values (ASV) were determined and used to rank tested potato clones based on their stability. The yield stability index (YSI) and rank sum (RS) were calculated as: YSI = RASV + RY, where RASV is the rank of the AMMI stability value and RY is the rank of the mean tuber yield of a genotype across environments (Adjebeng-Danquah et al. 2017).

Results

Yield performance

The analysis of variance revealed significant effects of clone, site, season, clone × site, clone × season, site × season, and clone × site × season on marketable and total yields of potato tubers (Table 2).

Among tested potato clones, the highest number of tubers per plant (9.38 tubers per plant) was observed on CIP393280.64, while the clone CIP398190.615 produced a low number of tubers per plant (7.64 tubers per plant) (Table 3). The clones CIP396018.241, CIP396018.241, CIP393077.159, CIP393371.58, and CIP393280.64, showed the yields ranging between 21 and 31 tons/ha, while the local checks Kirundo and Kinigi revealed the yields of 30 and 35 tons/ha, respectively. In the first season, across 15 sites, among new tested potato clones, the highest yield of 22.67 ton/ha was observed on CIP393371.58. This yield was in the same range as the yield of local checks, 21.76 and 25.95 tons/ha for Kinigi and Kirundo, respectively (Table 3). In the second growing season, the potato clone CIP393371.58 revealed the highest yield of 46.2 tons/ha, compared to local check, Kirundo with 44.79 tons/ha and Kinigi with 38.13 tons/ha. The clones of CIP396018.241, CIP393077.159, and CIP393280.64, showed the yield ranging between 30 and 32 tons/ha (Table 3). Across all sites, in both growing season, the clones CIP393077.159, CIP393371.58, and CIP393280.64 revealed the yields of 31.09, 27.72. and 27.68 tons/ha that fall in the same range of yields as local checks Kinigi and Kirundo with 29.94 and 35.15 tons/ha, respectively (Table 3). The season two (Season A starting from August 2018 to December 2019) revealed the highest total yield compared to the season one (Table 3).

In terms of trial sites, the sites with high yields were Cyuve, Kigeme, and Uwinkingi, that produced 43.79 tons/ha, 36.56 tons/ha and 34.38 tons/ha, respectively. The lowest yielding trial sites were Kayonza with 18.17 tons/ha (Table 4).

Stability and adaptability

The clone of CIP393280.64 revealed the lowest AMMI stability value (ASV). Its ASV was 1.41. This clone was followed by variety Kinigi with ASV of 2.72 and CIP398190.615 with AVS of 2.84. The tested plant materials with the highest AVS was Kirundo with 9.55 and CIP393077.159 with 5.34 (Table 5). Based on YSI ranking combining high yield and stability, the first four genotypes were Kirundo, CIP393077.159, CIP39601.241, and CIP393371.58 with YSI of 16.6, 11.3, 9.1, and 7.3, respectively. The last genotype was CIP393280.64 with YSI of 2.4 (Table 5).

First four Additive Main Effects and Multiplicative Interaction (AMMI) selections per environment are detailed in Table 6. The local variety Kirundo was the first in twelve environments, while among new tested clones, the only clone CIP393077.159 was the first in two environments. The clone CIP393077.159 was the second in four environments, the clone CIP393371.58 was the second in three environments, Kinigi was the second in six environments while Kirundo was the second in one environment. For the third positions the clone CIP393371.58 came in five environments, the clone CIP393077.159

Table 2 F-test statistics of ANOVA of yield components of five new potato clones and two local checks (Kinigi and Kirundo), assessed at fourteen sites in two growing seasons

Source of variation	Df	Number of tubers per plant	Marketable tuber yield	Unmarketable tuber yield	Total tuber yield
Replication	2	91.78	427.73	5.78	467.28
Clone	6	473.75**	11,518.93**	34.18ns	12,174.91**
Site	13	1505.67**	28,557.05**	893.75**	28,282.11**
Season	1	3412.74**	46,859.43**	89.63**	51,047.96**
Clone × Site	78	1411.18ns	13,593.68**	387.14ns	14,437.92**
Clone × Season	6	217.20*	2296.69**	84.28*	2848.51**
Site × Season	13	1975.03**	33,561.06**	391.05**	36,145.29**
Clone × Site × Season	78	1508.97*	8773.83**	435.50ns	9375.36**
Residual	390	5451.03	23,672.87	2037.19	25,787.89
Total	587	16,047.36	169,261.29	4358.51	180,567.23

Df: degree of freedom, *p = 0.05, ***p = 0.001, ns: non significant

Table 3 Average yields (tons/ha) of five new potato clones and two local checks (Kinigi and Kirundo) across two growing seasons and fourteen trials sites in Rwanda

Site	Number tubers per plant			Marketable yield			Unmarketable yield			Total yield		
	Season 1	Season 2	Average	Season 1	Season 2	Average	Season 1	Season 2	Average	Season 1	Season 2	Average
CIP393077.159	4.93	11.28	8.11^{a}	16.76	40.12	28.44^{c}	1.63	3.69	2.66a	18.39	43.80	31.09^{c}
CIP393280.64	7.26	11.51	9.38^{bc}	14.66	35.20	24.93^{b}	2.70	2.88	2.79a	17.36	38.08	27.72^{b}
CIP393371.58	6.42	8.98	7.70^{a}	20.28	30.26	25.27^{b}	2.39	2.43	2.41a	22.67	32.69	27.68^{b}
CIP39601.241	5.62	10.09	7.86^{a}	8.90	27.52	18.21^{a}	2.70	2.54	2.62a	11.60	30.06	20.83^{a}
CIP398190.615	4.90	10.38	7.64a	9.90	29.68	19.79^{a}	2.18	3.47	2.83a	12.09	33.15	22.62^{a}
Kinigi	6.43	10.87	8.65^{ab}	19.30	34.95	27.12^{bc}	2.45	3.18	2.82a5	21.76	38.13	29.94^{bc}
Kirundo	7.10	13.30	10.20^{c}	23.37	40.42	31.90^{d}	2.58	3.93	3.26a	25.95	44.35	35.15^{d}

Mean values followed by the same letter(s) within the column are not significantly different at 5% level of least significant difference (LSD) test

Table 4 Average yields (tons/ha) of five new potato clones and two local checks (Kinigi and Kirundo) across fourteen trials sites for two growing seasons in Rwanda

Site	Potato clone or variety							Average
	CIP393077.159	CIP393280.64	CIP393371.58	CIP39601.241	CIP398190.615	Kinigi	Kirundo	
Busasamana	26.46	21.19	27.31	16.94	11.07	30.98	49.10	26.15^{b}
Cyuve	57.77	47.58	38.10	31.08	25.28	46.60	60.08	43.79^{d}
Jenda	18.92	19.57	20.70	13.23	5.49	26.05	27.04	18.71^{a}
Kabatwa	19.62	17.36	13.47	22.31	10.25	24.18	33.19	20.05^{a}
Karongi	27.38	22.96	31.92	21.71	22.71	27.58	37.45	27.39^{b}
Kayonza	29.41	17.42	20.66	8.20	16.81	15.77	18.94	18.17^{a}
Kigeme	41.92	40.65	27.94	26.73	45.45	32.88	40.38	36.56^{c}
Kisaro	24.92	25.33	28.68	15.91	20.93	28.66	29.41	24.83^{b}
Mukura	43.21	38.62	35.98	31.88	28.29	33.44	27.32	34.10^{c}
Nyabimata	30.99	25.94	24.45	23.17	28.79	23.33	29.34	26.57^{b}
Nyabirasi	25.61	19.69	28.90	15.07	22.93	30.56	32.03	24.97^{b}
Ruhunde	29.06	26.63	26.46	21.27	22.81	35.31	33.58	27.87^{b}
Rwamagana	24.48	27.50	30.26	17.27	27.16	26.91	32.03	26.52^{b}
Uwinkingi	35.57	37.61	32.71	26.86	28.70	36.95	42.27	34.38^{c}
Average	31.09^{c}	27.72^{b}	27.68^{b}	20.83^{a}	22.62^{a}	29.94^{bc}	35.15^{d}	

Mean values followed by the same letter(s) within the column, and within the row are not significantly different at 5% level of least significant difference (LSD) test

Table 5 AMMI stability values, yield stability index and ranking of new potato clones and varieties across 14 environments in Rwanda

Genotype	Mean	AMMI ranking	Stability (ASV)	YSI	YSI ranking
Kirundo	49.89	7	9.55	16.6	1
CIP393077.159	41.83	6	5.34	11.3	2
CIP39601.241	29.49	5	4.05	9.1	3
CIP393371.58	36.68	4	3.27	7.3	4
CIP398190.615	28.3	3	2.84	5.8	5
Kinigi	39.32	2	2.72	4.7	6
CIP393280.64	34.21	1	1.41	2.4	7

came in three environments, the clone CIP393280.64 appeared in three environments, the variety Kinigi occupied the third position in two environments, while the clone CIP398190.615 occupied the third position in one environment. The clones CIP393077.159 was the fourth in three environments, the clones CIP393280.64 and CIP396018.241 were the fourth in two environments, the variety Kinigi occupied the four positions in four environments, while the clone CIP393371.58 was the fourth in one environment.

Tuber characteristics and processing qualities

The results of tuber characteristics and processing qualities are detailed in Table 7. The potato with high number of deep eyes was CIP393077.159, CIP396018.241, and the local variety Kinigi. The others clones and Kirundo revealed shallow eyes. A high number of eyes was observed on clones CIP393077.159, CIP393280.64, CIP393371.58, and Kinigi. The other clones, including CIP396018.241, and CIP398190.615, and local check Kirundo revealed a low number of eyes. All new tested potato clones revealed a dry matter content that is above 18% of total fresh weight except CIP396018.241 which has 17.1% of fresh weight. The variety Kinigi revealed the highest dry matter content (19.2%), while Kirundo showed the lowest dry matter content (16.8%). Based on the crisps color, the clones CIP393077.159, CIP393280.64, CIP396018.241, CIP398190.615 showed the same trend as local check Kinigi. The color of crisps from CIP398190.615 showed a clearer color compared to crisps from local checks Kinigi and Kirundo. The conversion factor of clones CIP393280.64, CIP393077.159, CIP396018.241, and CIP398190.615 was as low as the conversion of Kinigi. This conversion was 4.1, 3.8, 4.8, 4.4, and 4.2 kg of potato for one kilogram of crisps, respectively. The crisps from these clones were ranked as good or very good for taste and crunch.

Discussions

Yields of tested potato clones and varieties at fourteen sites in two growing seasons

Yield is among the main farmers' preferred crop traits, but it is influenced by many factors (Muhinyuza et al. 2012). The genetic makeup of each plant variety, environment factors such water, temperature, soil fertility,

Table 6 First four AMMI selections per environment of five new potato clones and two local checks (Kinigi and Kirundo) for tuber yield (t/ha) across 14 environments for two seasons in Rwanda

No	Environment	Agro-ecology	Mean	Score	Ranking			
					1	2	3	4
1	Kisaro	Buberuka Highlands	35.8	0.81	Kirundo	CIP393077.159	Kinigi	CIP393371.58
2	Ruhunde		45.28	− 0.15	Kirundo	Kinigi	CIP393077.159	CIP393280.64
3	Muko	Cental plateau	48.48	− 2.97	Kirundo	CIP393371.58	Kinigi	CIP393077.159
4	Karongi	Congo Nile watershed divine	42.02	− 0.08	Kirundo	CIP393077.159	CIP393371.58	Kinigi
5	Kigeme		57.57	− 1.63	Kirundo	CIP393371.58	CIP393077.159	Kinigi
6	Mukura		47.54	4.6	CIP393077.159	CIP393371.58	CIP398190.615	CIP393280.64
7	Nyabimata		35.24	− 2.41	Kirundo	Kinigi	CIP393371.58	CIP393077.159
8	Nyabirasi		36.18	0.46	Kirundo	CIP393077.159	CIP393371.58	Kinigi
9	Uwinkingi		51.9	0.47	Kirundo	CIP393077.159	CIP393371.58	Kinigi
10	Kayonza	Eastern savanna	16.43	0.17	Kirundo	Kinigi	CIP393077.159	CIP393280.64
11	Rwamagana		18.11	1.95	CIP393077.159	Kirundo	CIP393371.58	Kinigi
12	Busasamana	Virunga	35.87	− 1.58	Kirundo	Kinigi	CIP393280.64	CIP393077.159
13	Jenda	Virunga	18.92	− 0.04	Kirundo	Kinigi	CIP393280.64	CIP396018.241
14	Kabatwa	Virunga	30.09	0.39	Kirundo	Kinigi	CIP393280.64	CIP396018.241

Table 7 Results of tuber characteristics and processing qualities of five tested new potato clones and local varieties Kinigi and Kirundo

ID Clone	Shape (oval)	Eyes type	Eyes nbr	sp.gr	DMC (%)	Color	Taste	Crunch	Conversion factor (kg of potato per kg of crisps)	General comments
CIP393077.159	Round	Deep	More	1.06	18.2	3,1,2,1	Good	Good	4.1	Good
CIP393280.64	Round	Shallow	More	1.07	18.4	1,2,3,1	Good	Good	3.8	Good
CIP393371.58	Round	Shallow	More	1.07	18.4	3,4,5,6	Bad	Bad	9.8	Bad
CIP396018.241	Round	Deep	Few	1.06	17.1	1,2,3,1	Good	good	4.8	Very good
CIP398190.615	Long	Shallow	Few	1.07	18.4	1,2,3, 2	Bad	Good	4.4	Very good
Kirundo	Round	Shallow	Few	1.06	16.9	3,3,2,2	Good	Bad	6.6	Bad
Kinigi	Round	Deep	More	1.08	19.2	3,1,2,1	Good	Very good	4.2	Very good

sp.gr: Specific gravity; DMC: Dry matter content

pH, season, and others, and genotype by environment interaction affect the crop yield in different ways (Patel et al. 2008). In a study to determine the performance and yield stability of two genotypes from a population, and three control cultivars; a variation in tuber yields among genotypes, locations and cropping seasons was reported, but the differences between locations and seasons were not significant (Mulema et al. 2008). According to Tessema et al. (2020), the genotype and environment and their interaction had considerable influence on quality and quantity of potato tuber yield. Variety effects were significant for all tested traits except total number of potato tubers. In the same study local varieties showed a high performance compared to new varieties (Fantaw et al. 2019; Gebreselassie et al. 2016). Rukundo et al. (2019) reported that the significant difference in total yields among potato genotypes is attributed to the intrinsic yield potential of genotypes, growing environment, and the interaction of genotype × environment. The results from this study agreed with previous findings. The analysis of variance revealed significant effects of clone, site, season, clone × Site, clone × Season, Site × Season, and clone × Site × Season on marketable and total yields of potato tubers. The effects of interaction of clone and Site on number of tubers per plant, effects of clones, and interaction effects of clone × Site, and clone × Site × Season on unmarketable tuber yields were not significant (Table 2). The variation in the genetic makeup of tested genotypes, and variation in soils characteristics and nutrients, and micro-climates of trial sites had high effects on observed yield variations. Crop genotypes have different capacity to absorb and use soil available nutrients, therefore, in the variety selection process, the adaptability of tested genotypes has to be determined in order to recommend to farmers a variety with specific or broad adaptability.

Potato genotypes significantly differed in their number of tubers per plant across of all locations. The highest number of tubers per plant (9.3 tubers per plant) was observed on CIP393280.64 clone, while the clone CIP398190.615 produced low number of tubers per plant (7.6 tubers per plant) (Table 3). According to Patel et al. (2008) and Subarta and Upadhya (1997), the variations among the genotypes for number of tubers per plant is associated with the inherent potential of variety which is highly influenced by growing conditions and interaction of variety by environment. This was also highlighted by Firman and Daniels (2011) reporting that a high number of tubers per plant is affected by varietal characteristics, adaptability or effects of the other growth attributes. Through their study to identify the influence of soil types on a number of tubers per plant, it was noticed that the number of tubers was consistently lower with clay than other soil types. The greatest average number of tubers per plant was observed in sandy soil. The variation in the number of tubers per plant observed among tested potato clones, are a result of variation in the genetic makeup of tested clones, sites, seasons, and their interaction. Therefore, in the selection process, the best clones should have a high yield with a high number of marketable tubers.

The clones of CIP396018.241, CIP398190.615, CIP393077.159, CIP393371.58, and CIP393280.64, showed yields ranging between 20.83 and 31.09 tons/ha, while the local checks Kirundo and Kinigi revealed the yields of 29.94 and 35.15 tons/ha, respectively (Table 3). The observed average yields of the studied clones across all sites and seasons are within the yield range of potato varieties that have been released in Rwanda (CIP 2009). The potato tubers yield ranging between 21.7 and 40.3 tons/ha was reported by Mulema et al. (2008). This showed that the tested clones are good candidates for future new potato varieties in Rwanda.

Across all sites, in both growing season, the clones CIP393077.159, CIP393371.58, and CIP393280.64 revealed the yields of 31.09, 27.72. and 27.68 tons/ha, respectively, that fall in the same range of yields as local checks Kinigi and Kirundo with 29.94 and 35.15 tons/ha, respectively (Table 3). The good yield performance of local checks is mostly associated with their adaptation to the local environmental conditions. Therefore, the good performance of new tested genotypes revealed their relative adaptation to Rwandan environment.

The season two that is a season A in Rwanda, starting from August–December), revealed the highest total yield compared to the season one (season B in Rwanda, starting from February to July) (Table 3). This difference in the yield performance between season A and B might be due to factors associated with this season. According to Mulema et al. (2008), the season A and B do not have the same rainfall, temperature, solar luminosity, and air humidity. It was suggested that the drought stress has a negative impact on tuber bulking and consequently tuber yield (Aliche et al. 2018; Lahlou, et al. 2003). Previous studies have indicated that inadequate water during the critical periods of tuber bulking may lead to low tuber yield and quality defects (Martin et al. 1992; Mulema et al. 2008; Subarta and Upadhya 1997). These observations concur with results from this study. In Rwanda it is known that the season A is the main agriculture season. The causes of low potato tubers yield observed in season B are associated with a low rainfall and water stress occurred in the season B. The results from both seasons across all trial sites showed that among new evaluated clones, CIP393371.58 and CIP393077.159 revealed a high yield potential.

In terms of trial sites, the sites with high yields were Cyuve, Kigeme, and Uwinkingi, that produced 43.79 tons/ha, 36.56 tons/ha and 34.38 tons/ha, respectively (Table 4). These results are within the findings reported by NISR (2019) and Rukundo et al. (2019) who mentioned that the highland zone of Virunga (Cyuve) and the highland of Congo/Nile watershed Divine are the main potato producer zones in Rwanda due to their favorable soil and climatic conditions. The lowest yielding trial sites were Kayonza with 18.17 tons/ha that is located in the low rainfall prone area (Table 4). The finding of this study revealed that any investor targeting the commercial production of potato in Rwanda should orient his business in highland zones. If the low rainfall areas are his target, he has first to invest in the establishment of irrigation facilities.

Adaptability of tested potato clones and varieties across fourteen environments in Rwanda

In the additive main effects and multiplicative interaction (AMMI) approach (Gauch and Zobel 1988), a genotype with the least absolute value of ASV score is the most stable (Kundu et al. 2020; Purchase et al. 2000). The clone of CIP393280.64 is the most stable with the lowest AMMI's stability value (ASV) of 1.41, followed by variety Kinigi with ASV of 2.72 and CIP398190.615 with AVS of 2.84. These genotypes revealed a broad adaptability across trial sites. The genotype Kirundo showed the highest ASV of 9.55 followed by CIP393077.159 with 5.34 and CIP39601.241 with 4.05 (Table 5). The variety Kirundo with good performance across all agro-ecological zone indicates its broad adaptability while other tested genotypes revealed a specific adaptability.

First four AMMI selections per environment showing the recommendable genotypes for each environment is shown in Table 6. The clone CIP393077.159 was promising at Busasamana, Karongi, Kayonza, Muko, Nyabimata, Nyabirasi, and Ruhunde. The clone CIP393371.58 was promising at Karongi, Kigeme, Kisaro, Mukura, Nyabimata, and Nyabirasi. The CIP393280.64 was promising at Busasamana, Jenda, Kabatawa, Kayonaza, and Mukura. The clone CIP396018.241 was promising at Jenda, and Kabatwa, while the clone CIP398190.615 was only promising at Mukura. About the local checks Kirundo and Kinigi revealed to be promising in all tested trial sites except Mukura. The results of this study approved the importance of use of Kinigi and Kirundo as lock checks in evaluation and selection of new potato clones in Rwandan agro-ecological zones.

Processing qualities of five new tested potato clones and local varieties Kinigi and Kirundo

The shape and size of the tubers, eye depth, average weight, total potato defects, specific gravity and dry matter content of potatoes are key characteristics determining their processing appropriateness (Afroj and Bashar 2017; Werij 2011). Tubers with medium to large size, and shallow eyes are the most preferred by processors because of low losses during peeling. Through this study, the potato clones or variety with high number of deep eyes were CIP393077.159, CIP396018.241, and the local variety Kinigi. The others clones and Kirundo revealed shallow eyes (Table 7).

The flesh tuber colour is also an important attribute. Potato tubers with golden yellow flesh colour and high dry matter content are the best for high quality potato crisps and chips (De Haan et al. 2014). The dry matter content is very important characteristic for roots and tubers varieties for processing. However, this trait is significantly affected by the environment (Hamouz et al. 2005; Tsegaw 2011). In this study, all new tested potato clones revealed a dry matter content that is above 18% of total fresh weight except CIP396018.241 which has 17.1% of fresh weight. The variety Kinigi revealed the highest dry matter content (19.2%), while Kirundo showed the lowed dry matter content (16.8%) (Table 7). From this study, four of the five tested clones CIP393280.64, CIP393371.58, CIP398190.615, and CIP393077.159 have a dry matter content that meets the processor needs comfortably.

It is known that a good potato variety for processing should contain low reduced sugar content. The increased level of reducing sugar content in potato tubers resulted a dark and unacceptable chip colour (Ezekiel et al. 2007). Based on the crisps color, the clones CIP393077.159, CIP393280.64, CIP396018.241, CIP398190.615 showed the same trend as local check Kinigi that is the most popular variety for chipping in Rwanda. The color of crisps from CIP398190.615 showed a clear color compared to crisps from local checks Kinigi and Kirundo. This is an indication that these clones have a low reducing sugar content, and this leads to the acceptable crisp color. Therefore, it can be deduced that clones CIP393077.159, CIP393280.64, CIP396018.241, and CIP398190.615 have a low reducing sugar content, consequently, good candidate for processing.

A conversion factor indicate the quantity of tubers needed to produce one kilogram of crisps. The conversion of clones CIP393280.64, CIP393077.159, CIP396018.241, and CIP398190.615 was as low as the conversion of Kinigi. This conversion was 4.1, 3.8, 4.8, 4.4, and 4.2 kg of potato per 1 kg of crisps, respectively (Table 7). The crisps from these clones were ranked as good or very good for taste and crunch. Based on taste, conversion, color, and crunch, clones CIP396018.241, and CIP398190.615 are able to produce crisps as good as Kinigi, the most popular variety for chipping in Rwanda. The clones CIP393077.159 and CIP393280.64 produced acceptable crisps. The final processing results showed that all clones except CIP393371.58 have good processing traits. When these varieties are released, they will give processing firms alternatives raw materials. Moreover, hotels, and restaurants as well as households will have more choice of potato varieties.

Conclusions

The yield results from five clones studied for two seasons showed that the newly tested clones CIP393371.58 and CIP393077.159 have relatively high yield potential and broad adaptability. The clones of CIP393077.159, CIP39601.241 and CIP393371.58 had a high yield and stability compared to the other clones tested. Based on the number and type of eyes, dry matter content, color of processed crisps, taste, conversion ratio, and crunch we found that clones CIP396018.241, and CIP398190.615 were suitable to produce very good crisps as Kinigi, the most popular variety used for French fries. This study showed that CIP393077.159 and CIP393280.64 can also be used to produce crisps that are also acceptable. Considering the processing qualities, and yield stability, all the five tested clones selected from the 43 initial clones can be recommended for release as commercial varieties. Any time they are released, they will give processing firms alternative raw materials, and hotels, restaurants and households more choice of potato varieties for French fries.

Author contributions

This manuscript is a result of joint efforts: NT have coordinated the trials across the country. EV and NJC have provided facilitations to conduct the trials.

MT has analyzed the collected data, and RP drafted the manuscript and all authors have provided their inputs. All authors read and approved the final manuscript.

Funding
This study was funded by PSDAD (Award No. 0112/IRG/05/2017 of Value Chain Competitiveness Fund).

Declarations

Competing interests
The authors declare that they have no competing interests.

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Received: 3 March 2022 Accepted: 16 May 2022
Published online: 16 June 2022

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