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Progress Made in Developing New High Yielding Potato Varieties for the Kenyan Highlands at KALRO-Tigoni

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Abstract: Breeding has been going on at Kenya Agricultural and Livestock Research Institute (KALRO), Tigoni in Kenya to develop high yielding potato varieties that have good processing qualities. The objective was to develop high yielding potato varieties that are adapted to the Kenyan climatic and environmental conditions and that are suitable for processing. After initial crossing, the resultant families were evaluated for yield as well as crisping and chipping quality for three consecutive generations at KALRO-Tigoni; this resulted in selection of 112 candidate clones. The 112 selected clones (52 potentially for crisping) were then evaluated under Advanced Yield Trials (AYT) during the 2015 short rains season and 2016 long rains season at three sites (Tigoni, Molo and Meru). Yield data was analysed using the lattice procedure of Statistical Analysis Systems (SAS 9.1) statistical package. Genotype x Environment Interaction (GEI) as well as stability and adaptability of potato clones across sites was analysed using additive main effects and multiplicative interaction (AMMI) and genotype main effect and Genotype x Environment Interaction (GGE) biplot analysis. In the AYT, significant Genotype x Environment Interactions (GEI) were observed. Clone G6 (2E87) was closest to the ideal genotype; it was the highest yielding and most stable while environment 2 (long rains season 2016 at KALRO-Tigoni) was the closest to ideal environment and therefore the most desirable of the six environments. From AYT, 18 clones were selected, 11 of them good for crisping. These clones were recommended for the National Performance Trials (NPT) before release of new varieties.

Keywords: Advanced Yield Trials, KALRO-Tigoni, Kenya, Potato Breeding

Introduction

Background

In Kenya, potato is an important food crop, second after maize in volumes produced (MoA, 1998; FAO, 2013; 2014). The crop is grown mainly as a cash and food crop by small-scale farmers, although some larger-scale growers specialize in commercial production (FAO, 2014). Potato therefore plays an important role in food security (MoA, 2005; 2008; FAO, 2014) and is grown by about 800 000 farmers, on 158 000 ha per season, with an annual production of about 1.2 million tonnes in two growing seasons (Riungu, 2011; FAO, 2013; 2014; NPCK, 2014). The annual potato crop is valued at KES 13 billion (USD 150 million) at farm gate level and KES 40 billion (USD 362 million) at the consumer level (FAO, 2013; ANN, 2009). Potato farming in Kenya employs 3.3 million people at all levels of the value chain.

Potato therefore plays an important role in national food security and could ease pressure off the main cereal, maize. However, there has been a decline in potato production in Kenya (Gregory *et al*., 2013) because of a number of production constraints. These include low soil fertility, an inadequate supply of certified seeds, pests and diseases, low and erratic rainfall patterns as result of climate change and, the use of low yielding varieties (FAO, 2013).

There has been a long tradition of potato breeding in Kenya; screening and evaluation of imported European varieties and advanced clones from the International Potato Center (CIP) have been the most important

sources of new varieties. Work done on potato breeding in Kenya in the sixties and seventies concentrated on major gene resistance to late blight; the varieties were meant for production in the high altitude areas of Kenya (MoALF, 2016). From these efforts, fourteen potato varieties from Western Europe were released in Kenya through the national potato research programme. However, these varieties were not well adapted to the local agro-climatic conditions mainly because they were the long-day *Solanum tuberosum subsp. tuberosum* (MoALF, 2016). In addition, these varieties had little resistance to late blight caused by *Phytophthora infestans*; the disease is a very serious production constraint throughout all the potato growing regions in Kenya. Furthermore, these potato varieties were very susceptible to bacterial wilt caused by *Ralstonia solanacearum*; the disease is becoming increasingly important not only in the low and medium potential areas but also in the high potential areas (Muthoni *et al.*, 2013; MoA, 2005).

Between 1986 and 1997, adaptive research work was conducted at various stations in Kenya as a collaborative project between Kenya Agricultural Research Institute (KARI) and CIP. The main aim of these collaborative activities was to develop potato varieties with durable resistance to late blight, some level of tolerance to bacterial wilt and acceptable agronomic and post-harvest qualities (FAO, 2013). These activities were carried out at the highland stations of KARI Tigoni and Mau Narok, at the mid-altitude stations of KARI Embu, KARI Kakamega and KARI Kabete and at low-altitude stations of KARI Mtwapa, Shimba Hills and KARI Katumani. The collaborative work resulted in the release of varieties Tigoni (for processing) and, Kenya Furaha and Asante (for domestic consumption). Subsequent collaboration with CIP resulted in release of 7 more varieties by 2010 (MoALF, 2016). Interestingly, a farmer variety, *Shangi,* which was formally released in Kenya in 2015, is the most popular and is grown by over 70% of potato farmers (Muthoni *et al.,* 2013). Although the variety is fast maturing, it may not be best suited for processing industry.

Availability of suitable potato varieties for processing is important for the expansion of the processing sector in Kenya. The physical tuber quality, dry matter content and harvest maturity of potatoes are the determinants of the processing quality. The tuber shape, size and eye depth are important with regard to the appearance of the tubers and they determine the wastage that occurs during peeling (PSDA, 2009). Round tubers are preferred for crisping (chipping) while for making French fries, oval-shaped tubers are preferred. Currently, there is only one variety for making chips (French fries) (Tigoni) and one for making crisps (chips) (Dutch robyjn). However, Dutch robyjn is very susceptible to late blight, it is low yielding and has deep eyes leading to losses during peeling (PSDA, 2009). For the open air markets, white varieties are not preferred as they green easily.

Despite previous breeding efforts and import of seed potatoes from European countries, the impact of over 50 officially registered potato varieties in Kenya has not been realized. Imported varieties may not be well adapted to local conditions and may need high input levels for production. This may not be tenable especially with poor small scale farmers in Kenya. In addition, some of the imported varieties have been developed by private breeders and as such, issues of plant breeders' rights might hinder small scale farmers from engaging in commercial production of seeds of such varieties. There is need for continuous development of more locally adapted potato varieties that are high yielding and/or early maturing (for food security) and also to cater for the various processing industries. Consequently, development of new potato varieties was reinitiated with the reintroduction of cross-breeding activities in the national potato programme at KALRO-Tigoni (FAO, 2013). The objective of this research activity was to develop high yielding potato varieties that are adapted to the Kenyan climatic and environmental conditions and that are suitable for processing. The main focus is high yields, suitability for crisping and chipping and early maturity. Selection criteria are tuber yields (number and sizes), tuber shape, eye depth, skin colour and processing quality. Reported here are strides that have been made towards releasing new varieties.

Methodology

Study Site

The production of F1 potato seeds and the seedling multiplication were done at the Kenya Agricultural and Livestock Research Organization, Tigoni (KALRO-Tigoni) [The organization was formerly Kenya Agricultural and Research Institute, KARI]. The KALRO-Tigoni station is located 40 km north-west of Nairobi city centre, at an altitude of 2051 m above sea level (masl) latitude of 10 9'7.22" South and longitude 36°41'8.72" East (Jaetzold *et al*., 2006). The average annual rainfall is 1096 mm with a bimodal distribution. The long rainy season occurs between March and May, while the short rainy season is between October and December (Jaetzold *et al*., 2006). The mean annual air temperature is 18°C and ranges between 12 and 24°C. The soil type is humic-nitosol (alfisol) derived from quartz trachyte (Jaetzold *et al.*, 2006). The soil is very deep and well drained with a pH range of 5.5 to 6.5. The soil is of medium inherent fertility with organic carbon content of 1.65%. Exchangeable bases of potassium, calcium and magnesium are moderate to high with available potassium being about 21.2 ppm (Jaetzold *et al*., 2006).

Table 1: Name and source of the 14 potato parents used in the study

Parent	Germplasm maintainer	Male/Female
Shangi	KALRO-Tigoni	Male
Kenya Karibu	KALRO-Tigoni	Male
Tigoni	KALRO-Tigoni	Male
Sherekea	KALRO-Tigoni	Male
Meru Mugaruro	KALRO-Tigoni	Male
Kihoro	KALRO-Tigoni	Male
Ingabire	KALRO-Tigoni	Male
Bishop Gitonga	KALRO-Tigoni	Male
391919.3	CIP	Female
394904.9	CIP	Female
394905.8	CIP	Female
392278.19	CIP	Female
394895.7	CIP	Female
394903.5	CIP	Female

CIP = International Potato Center, KALROI-Tigoni = Kenya Agricultural and Livestock Research Organization, Tigoni

Plant Materials

The study used 48 potato families developed as follows: Eight potato varieties selected previously from a bacterial wilt screening trial (Muthoni *et al.,* 2014) were used as males. The eight varieties are high yielding and are popularly grown by Kenyan farmers but are highly susceptible to bacterial wilt (Muthoni *et al*., 2014). These males were crossed to a set of six female clones sourced from the International Potato Center (CIP) in Peru using a North Carolina mating design II (Table 1). Crossing was done to generate 48 families. Crossing was done in the field during the short rains season of 2012.

Generation of True Potato Seed and F1 Seedlings

A few days after crossing, berries started forming on successful crosses and about 40 days later, they were harvested. The harvested berries were stored in khaki paper bags for three weeks to soften before processing. The ripened berries were processed by cutting them with a knife and emptying the seeds into a basin containing clean water. The seeds were washed and then spread on filter papers and placed on a table in the laboratory to air-dry overnight. The following day, all the seeds from each cross family were soaked in 1500 ppm GA3 solution for 24 h to break dormancy. Thereafter they were rinsed and immediately sown in plastic trays containing sterilized sand. Watering was done using a can and the seedlings were sprayed against pests and diseases as required. Four weeks later, all the seedlings were transplanted from the plastic trays into the field at KALRO-Tigoni during the long rains season of 2013. Transplanting was done on 3rd April 2013.

Field Management of the Seedling Generation

The seedlings were transplanted in furrows at spacing of 75×30 cm. At transplanting, diammonium phosphate (DAP) (18% N: 46% P_2O_5) was applied at the recommended rate of 500 kg ha^{-1}. Weeding, ridging and pests and late blight control were carried out as per recommendations for potato production in Kenya (KARI, 2008). When the crop was mature, it was harvested, each plant separately. From each cross family, 240 plants were randomly selected and from each selected plant, one tuber was retained. To break tuber dormancy, the tubers were treated by dipping them in a big container containing GA3 at 5 ppm for ten minutes. Thereafter, they were air-dried and covered with a black polythene sheet for one month. They were then uncovered until sprouting.

Field Management and Selection of Clonal Generations

The sprouted tubers were planted out in the field at KALRO-Tigoni during the 2013 short rains season so as to give the first clonal generation crop. The experimental materials consisted of the 48 families. These were planted in a 6×8 alpha lattice design replicated three times. Each plot consisted of 80 plants i.e., 8 rows each consisting of 10 plants. The tubers were planted in furrows at a spacing of 75×30 cm. During planting, DAP (18% N: 46% P_2O_5) was applied at the recommended rate of 500 kg ha^{-1}. Weeding, ridging and pests and late blight control were carried out as per recommendations for potato production in Kenya (KARI, 2008). Supplemental irrigation was carried out when rainfall was not enough. When the crop was mature, it was harvested, each plant separately. At harvest, data collected were number of tubers per plant i.e. ware (>45 mm in diameter) and seed (<45 mm in diameter) and weight of different tuber sizes i.e., ware (>45 mm in diameter) and seed (<45 mm in diameter). These were taken on the 20 middle plants per plot. Other features considered in the selection were tuber shape, tuber skin colour, number of eyes per tuber, tuber eye depth and general visual appearance of the tubers. This data collection and selection was carried out by a team consisting of two breeders, two socioeconomists, a food scientist, an agronomist and three field technical officers in charge of basic seed potato production. These people, all working at KALRO Tigoni, are well informed on potato production systems in Kenya and the needs of various ware potato markets. Based on the above agreed selection criteria, entire cross families that were inferior were rejected; 18 families were rejected. Of the accepted 30 families, 50 superior plants were selected from each family; these translated to 50 clones per selected family.

The selected families were planted out in the field at KALRO-Tigoni during the 2014 long rains season to generate second clonal generation. Each family was represented by the 50 selected clones. Each plot consisted of 50 rows i.e., clones and there was no

replication. During harvesting, promising clones were selected. Selection of the promising clones was done in a participatory manner by stakeholders who were invited to undertake this exercise. The 40 stakeholders included the local farmers, traders from the local Limuru open air market, agricultural extension officers from Limuru sub county and local small-scale processors of chips and crisp. Selection criteria were tuber yields (numbers of different tuber sizes were counted), tuber shape, tuber eye depth, number of eyes per tuber and skin colour. Data was collected on the three middle rows per plot. These stakeholders selected a total of 542 clones across all the families.

In the following 2014 short rains season, the 542 clones were planted in the field at KALRO-Tigoni to give third clonal generation. All tubers in each of the clone selected in the second clonal generation were planted as one plot without replication. Field management of the crop was as in the previous generations. Supplemental irrigation was carried out when rainfall was not enough. Upon maturity, the crop was harvested. Yield data was taken i.e., total yield and the clones were later processed and tested for suitability for processing (crisps and chips) and fresh cooking (suitability for mashing). For crisping, chipping and fresh cooking evaluation, 5 kg of tubers from each clone were made into crisps, another 5 kg into chips and another 5kg were boiled. Once ready, the samples were set out on trays for organoleptic testing. A panel 50 people conducted the sensory evaluation. The panel consisted of some members of staff at KALRO-Tigoni, some casual field labourers and some students who were on practical training at KALRO-Tigoni. Based on yield (over 35 ton/ha), processing quality (crisps and chips) and fresh cooking (mashing quality), 112 clones were selected (52 potentially for crisping) (Table 4). These 112 clones were then multiplied at KALRO Tigoni for one season during the 2015 long rains season to increase potato tuber quantities (fourth clonal generation). Field management of the crop was as in the previous generations. Upon crop maturity, yields data was taken (Table 4).

After multiplication, the 112 clones were planted out for Advanced Yield Trials (AYT) and stability studies during the 2015 short rains season and 2016 long rains season at three sites (Tigoni, Molo and Meru). The three sites differed in seasonality (Table 2). The three sites and two seasons formed six environments in which the AYT and stability studies were undertaken (Table 3). At each site and each season, each clone was planted in one ten-meter row consisting of ten plants. Field management of the crop was as in the previous generations but there was no supplemental irrigation. Upon crop maturity in each site and each season, the clones were harvested and yield data collected.

Genotype x Environment Interaction (GEI) Analysis

AMMI Model

After harvesting advanced yield trials, yield data was subjected to Analysis of Variance (ANOVA) using the lattice procedure of Statistical Analysis Systems (SAS) statistical package (SAS, 2003) to determine the effects of environments, genotypes and Genotype x Environment Interaction (GEI) on potato tuber yields. Genotype stability was described using the Additive Main effects and Multiplicative Interaction (AMMI) model that combines into a single model analysis of variance (ANOVA) for genotype and environment main effects with Principal Component Analysis (PCA) for the GEI. The complete AMMI model is shown below (Crossa, 1990):

$$Y_{ij} = \mu + g_i + e_j + \sum_{k=1}^{t} \lambda_k \ \alpha_{ik}\gamma_{jk} + \varepsilon_{ij}$$

where, Y_{ij} = is the mean yield (t ha^{-1}) of the i^{th} genotype in the j^{th} environment, μ is the overall mean, g_i and e_j are the main effects of the genotype and environment respectively, t is the number of PCA axes considered, λ_k is the singular value of k^{th} PCA axis, α_{ik} and γ_{jk} are scores for the i^{th} genotype and j^{th} environment on the kth PCA axis and ε_{ij} is the residual term which includes experimental error.

Table 2: Seasonality at Tigoni, Meru and Molo sites

Site	Long Rains (LR) season	Short rains (SR) season
Tigoni	March-May	October-December
Marimba (Meru)	October-December	March-May
Marindas (Molo)	May-August	October-December

Table 3: Test environments in which advanced yield trials were conducted

Tigoni SR 2015	Tigoni LR 2016	Meru LR 2015	Meru SR 2016	Molo SR 2015	Molo LR 2016
ENVI 1	ENVI 2	ENVI 3	ENVI 4	ENVI 5	ENVI 6

SR = short rains season, LR = long rains season, ENVI 1 = short rains season 2015 at Tigoni, ENVI 2 = long rains season 2016 at Tigoni, ENVI 3 = long rains season 2015 at Meru, ENVI 4 = short rains season 2016 at Meru, ENVI 5 = short rains season 2015 at Molo, ENVI 6 = long rains season 2016 at Molo

Table 4: Potato clones selected in the third clonal generation based on mean yields and crisping, chipping and fresh cooking quality and their performance during fourth clonal generation

Third clonal generation						Fourth clonal generation		
Rank	Clone	Yields (ton ha^{-1})	Crisping	Chipping	Mashing	Rank	Clone	Yields (ton ha^{-1})
1	2E87	78.1				1	2E87	87.1
2	2C20	61.6				2	2C20	76.7
3	6GA	52.6				3	1EU	53.9
4	1EU	47.8	X			4	6GA	52.6
5	6CB	45.7				5	5E17	50.2
6	1EY	45.4				6	6CB	50.1
7	1HD1	44.3		X	X	7	1B5	48.8
8	5E17	44.2		X		8	6B17	48.2
9	2C56	44.2			X	9	2C56	48.0
10	1B5	44.1				10	1G45	46.7
11	6H17	43.9				11	4C19	45.9
12	1G45	43.9				12	5E08	45.5
13	2E68	43.6				13	1EY	45.4
14	5F38	42.7		X		14	1HD1	45.4
15	2HH	42.5				15	6H22	44.8
16	1EX	42.4	X			16	6D45	44.5
17	5E08	42.3				17	1EX	44.4
18	6B17	42.2				18	2B11	43.4
19	2B11	42.1				19	1B73A	43.1
20	1C7	42.0				20	1F9	43.0
21	5B26	41.6		X		21	2E68	43.0
22	UK 5	41.5				22	5B17	42.9
23	2H21	40.6				23	1B14	42.9
24	6H22	40.5				24	5C39	42.7
25	1B73A	40.1				25	2GC	42.6
26	1B14	39.9				26	1C7	42.4
27	2GC	39.6				27	6H49	42.3
28	1HC	39.6	X			28	5F38	41.7
29	1B67	39.5			X	29	2H21	41.6
30	1E02	39.5	X			30	5B26	41.6
31	1HG	39.4	X			31	5C5	41.6
32	6H49	39.2	X		X	32	2HH	41.5
33	2AB	39.1				33	UK5	41.5
34	1F9	39.0				34	1HG	41.4
35	1HB1	38.7	X			35	1EV	41.1
36	6BA	38.6			X	36	6B170	41.1
37	6C11	38.5				37	1E02	40.5
38	6C38	38.3				38	6H17	40.4
39	2F40	38.3				39	KE22	40.3
40	1B87	38.1				40	1B87	39.7
41	5B17	37.9				41	6D10	39.7
42	5C5	37.6				42	1HC	39.5
43	6D45	37.5	X			43	2C21	39.3
44	2C21	37.3				44	1B67	38.9
45	6C32	37.2		X	X	45	1HB1	38.9
46	5H61	36.9				46	2AB	38.8
47	6D12	35.8				47	6BA	38.7
48	6B90	35.3		X	X	48	3C22	38.6
49	5C44	35.3				49	2F40	38.4
50	1EV	35.1	X	X	X	50	1F15	38.4
51	5E07	35.0		X		51	5C44	37.8
52	6C25	34.9	X			52	6C11	37.7
53	5A2	34.8	X			53	3C21	37.6
54	5C21	33.3	X			54	UK 4	37.5
55	3F29	33.2			X	55	6C32	37.2
56	1B96	33.1	X			56	3E03	37.1

Table 4: Continue

57	1H1	32.9	X	X		57	5H61	36.9
58	3GA	32.6	X		X	58	6D47	36.9
59	2F35	32.6			X	59	5C21	36.8
60	UK 4	32.5	X			60	6C38	36.5
61	5E30	32.4		X		61	6H72	36.5
62	KE22	32.3	X			62	1HB	36.5
63	4DA	32.0	X			63	5E30	36.4
64	6D47	31.9	X			64	6B90	35.3
65	1G35	31.8	X			65	6D12	34.8
66	3H1	31.6		X		66	5A2	34.8
67	1F15	31.4		X		67	5C15	34.4
68	6C30	31.2	X		X	68	5E07	34.4
69	3C22	31.1	X			69	1H1	33.9
70	6D10	30.7	X	X		70	6C25	33.9
71	5C15	30.4	X	X		71	6GC	33.8
72	1HH1	30.0		X		72	1B96	33.1
73	4C19	29.9		X		73	3F29	32.2
74	1HB	29.7	X	X	X	74	3C48	31.7
75	1C48	29.6	X			75	6C30	31.2
76	6H78	29.6	X	X		76	3GA	31.2
77	5C39	28.5	X			77	2F35	30.6
78	1G31	28.4	X			78	1HH1	30.0
79	3E03	28.1		X	X	79	1C48	29.6
80	1G53	28.0			X	80	6H78	29.6
81	6C29	27.2	X			81	4DA	29.0
82	3C21	26.6				82	1G31	28.4
83	3F3	26.6	X	X		83	1F4	27.7
84	6GD	26.5	X			84	1G53	27.6
85	2F19	26.5			X	85	6C29	27.2
86	1HA1	26.4	X			86	1G35	26.8
87	3H17	25.9	X	X	X	87	3F3	26.6
88	6H58	25.9			X	88	6GD	26.5
89	6D43	25.8	X			89	2F19	26.5
90	1F6	25.8	X			90	1HA1	26.4
91	1F77	25.8	X			91	3H17	25.9
92	6GC	25.8			X	92	6H58	25.9
93	2C57	25.4	X			93	6D43	25.8
94	4E05	23.9	X			94	1F77	25.8
95	6D44	23.6	X			95	5F58	25.6
96	5F58	21.6		X		96	3H1	25.6
97	1F11	20.3	X			97	2C57	25.4
98	2H4	20.0	X		X	98	4E05	23.9
99	6B170	19.1	X			99	1F6	22.8
100	2C24	18.7	X			100	6D44	22.6
101	1F57	18.7	X			101	2C24	22.4
102	3C48	17.8		X		102	5E87	21.3
103	5H1	17.6	X			103	1F11	20.3
104	1F4	17.5	X		X	104	2H4	20.0
105	6B55	17.4	X			105	1F57	18.7
106	6B37	16.2		X		106	5H1	17.6
107	1C47	15.9	X			107	6B55	17.4
108	6H72	14.3		X		108	1H11	16.7
109	3C20	14.2	X			109	3C20	16.2
110	1HK	13.0	X	X		110	6B37	16.2
111	5E87	11.3	X			111	1C47	15.9
112	1HH	10.1		X		112	1HK	12.1
	Mean	33.1					Mean	35.7

From this model, AMMI Analysis of Variance (ANOVA) that showed significance of genotypes, environments and GEI was presented to interpret the results; also presented was the ranking of potato

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clones depending on their performance in different environments. The AMMI 2 showing the first and second Interaction Principal Components Axes (IPCA 1 and IPCA 2) was also presented to assess the interaction of the potato clones with the test environments.

GGE Biplot

Performance of potato clones across the environments was also explained using genotype main effect (G) and Genotype x Environment interaction (GGE) biplot analysis based on the principal component analysis (PCA) of environment-centred data (Yan *et al*., 2000; Yan, 2002). The GGE biplots display both Genotype (G) and Genotype x Environment (GE) interactions which are the two main sources of variation that are relevant for genotype evaluation (Kang, 1993; Yan *et al.,* 2007). The GGE biplot analysis was done using Genstat statistical package (14th Edition) (Payne *et al.*, 2011). The GGE mathematical model based on PCA of environment-centred data (which contains G and GE as the main sources of variation) subjected to Singular Value Decomposition (SVD) was used to visualize the relationship among potato clones and the environments. The basic model for a GGE biplot as described by Yan (2002) is:

$$Y_{ij} - \mu - \beta_j + \sum_{l=1}^{k} \lambda_l \ \gamma_{il}\eta_{lj} + \varepsilon_{ij}$$

Where:

Y_{ij} = Mean tuber yield (t ha^{-1}) of the i^{th} genotype in the j^{th} environment
μ = Overall mean
β_j = Main effect of the environment
λ_l = Eigen value associated with IPCA l
γ_{il} = The eigen vector of genotype i for PC l
η_{lj} = The eigenvector of environment j for PC l
ε_{ij} = Error term associated with potato genotype i in environment j.

Interrelationships among the test environments (Cooper *et al*., 1997) and potato clones (Yan *et al.*, 2001) were visualised using various GGE biplot graphs. A GGE polygon was used to identify high yielding clones in specific environments through analysis of the "which-won-where-pattern" (Yan *et al*., 2000; Yan, 2002). The GGE biplots based on Average Environment Coordination (AEC) and drawn on the genotype-focused biplot (Yan and Kang, 2003) was used to determine yield performance and stability of the 112 potato clones. Environment-focused scaling was used to test the relationship of the test environments.

Results

Selection of Potato Clones in Clonal Generations

Of the clones selected in the third clonal generation 50 clones (44.6%) had yields more than 35 ton ha^{-1} (Table 4).

During the fourth clonal generation, 64 clones (57.1%) yielded more than 35 ton ha^{-1} (Table 4). The fourth clonal generation had higher mean yield (35.7 ton ha^{-1}) than the third clonal generation possibly due to the higher rainfall which were experienced during the fourth clonal generation. As far as the yields were concerned, some clones ranked differently between the two clonal generations. For example 6D45, 1EU and 4C19 ranked differently between the two generations.

Stability Analysis of Clones in Advanced Yield Trials

AMMI Analysis of Variance

The AMMI analysis of variance showed significant ($p \leq 0.001$) effects of the genotypes (G), environments (E) and the G x E interaction (Table 5). Of the AMMI model (treatment) sum of squares, the genotypes contributed 41.52%, the environments 27.91% and the G x E interaction 30.56%. The IPCA1 was significant ($p \leq 0.001$) and it explained 10.76% of the treatment sum of squares which is 35.21% of the G x E interaction sum of squares. The IPCA 2 was also significant ($p \leq 0.001$) and it explained 7.77% of the treatment sum of squares which is 25.41% of the G x E interaction sum of squares. Combined, the IPCA 1 and IPCA 2 explained 60.62% of the total G x E interaction. Therefore AMMI 2 was used to describe the G x E interaction. The AMMI 2 utilizes the genotypic and environmental main effects to describe additive variation and two interaction principal component axes (IPCA 1 and IPCA 2) for the non-additive variation.

Ranking of the Best Four AMMI Selections Per Environment

There were differences in the ranking of potato clones for tuber yields across the six test environments (Table 6); this indicates crossover interactions. Environments 4, 1, 6 and 2 ranked clone G6 (clone 2E87) first.

Clone G6 (2E87) gave the highest mean yields across the six test environments (Table 7). Eight clones yielded more than 40 t ha^{-1}.

AMMI Biplots: Classification of Clones and Environments

Clone G20 was the winner in ENVI 1, ENVI 4 and ENVI 6 while clone G6 was the winner in the ENVI 2 (Fig. 1). Clone G6 showed a high and positive interaction with ENVI 2 whereas G47, G24, G52, G70 and G32 interacted positively with ENVI 3. Most potato clones had

IPCA values between +1.0 and -1.0 indicating low interaction with the test environments. The ENVI 1, ENVI 4 and ENVI 6 clustered together indicating similar performance of genotypes in these environments. In addition, the three environments showed low interactive behaviour with the test genotypes.

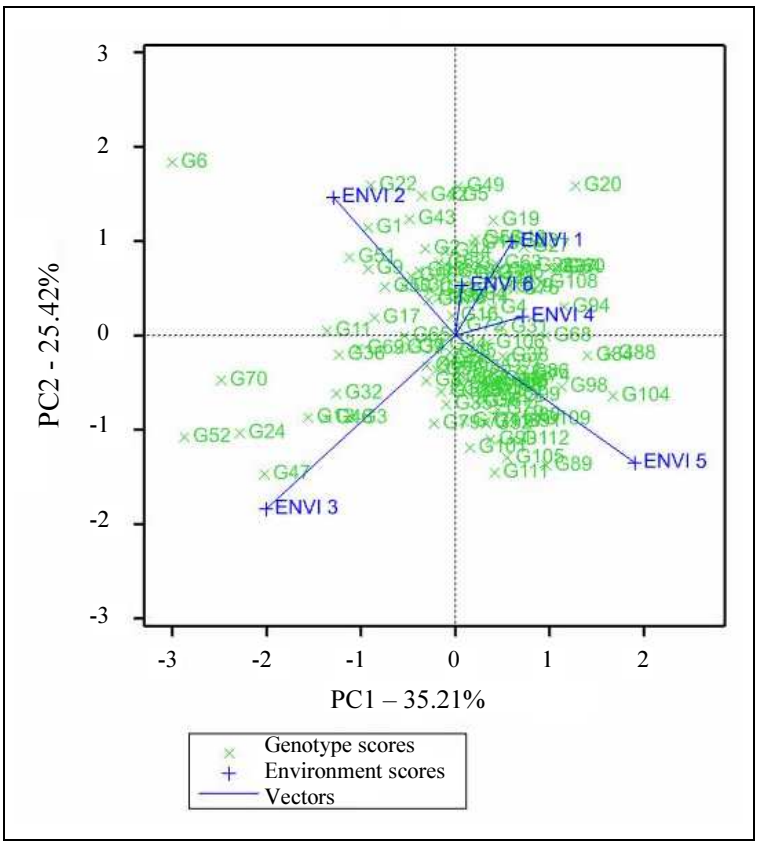

Fig. 1: AMMI 2 biplot of yields of 112 potato clones (G1-G112) across the six environments (ENVI 1-ENVI 6)

Table 5: Analysis of variance for potato tuber yields (t ha^{-1}) for 112 potato clones grown in six test environments

Source	d.f.	s.s.	m.s.	% treatment SS explained	% G x E interaction SS explained
Treatments	671	59464	88.62		
Genotypes (G)	111	24692	222.5***	41.52	
Environments (E)	5	16597	3319.4***	27.91	
Interactions (G x E)	555	18175	32.75***	30.56	
IPCA 1	115	6400	55.6***	(10.76)	35.21
IPCA 2	113	4619	40.9***	(7.77)	25.41
Interactions residuals	327	7156	21.9	(17.33)	39.37

df = Degrees of freedom; *** = Significant at p≤0.001; ns = Non significant; SS = Sum of Squares, MS = Mean Squares

Table 6: The best four potato clones from AMMI per environment

		Rank			
Environment	Mean yields (t ha^{-1})	1	2	3	4
ENVI 5	23.96	G61	G3	G47	G35
ENVI 4	27.53	G6	G47	G2	G3
ENVI 1	30.48	G6	G2	G3	G4
ENVI 6	38.25	G6	G47	G2	G3
ENVI 2	35.41	G6	G47	G2	G1
ENVI 3	35.27	G47	G52	G24	G6

Table 7: Performance of potato clones across the six environments

Genotype code	clone	Mean yields (t ha^{-1})	Rank
G6	2E+87	51.81	1
G47	4C19	48.1	2
G3	1EY	45.49	3
G2	1EX	42.98	4
G48	1F15	42.74	5
G24	2E+68	42.61	6
G52	1EU	40.84	7
G12	6B170	40.08	8
G4	6CB	39.47	9
G7	3E+03	39.38	10
G8	1HG	39.38	11
G1	5C39	39.31	12
G35	5E+17	39.26	13
G61	6D47	38.99	14
G70	3C48	38.73	15
G50	6D10	38.62	16
G32	3C22	38.58	17
G9	2HH	37.38	18
G25	1G53	37.02	19
G14	1EV	36.98	20
G18	1E+02	36.90	21
G15	1B73A	36.84	22
G51	6H78	36.79	23
G42	6H72	36.48	24
G13	6B17	36.42	25
G43	1B96	36.36	26
G69	1HB	36.25	27
G5	6D45	36.19	28
G10	1F9	35.80	29
G38	6D43	35.70	30
G31	5C5	35.54	31
G11	5F38	35.26	32
G77	1HC	35.24	33
G17	1G45	34.95	34
G46	1B87	34.95	35
G36	1HD1	34.61	36
G33	5E+07	34.35	37
G44	2F40	34.08	38
G75	3F3	34.03	39
G62	1B67	34.02	40
G39	6GA	33.61	41
G30	2C56	33.46	42
G80	2C24	33.38	43
G45	5C21	33.28	44
G65	6C38	33.21	45
G74	2F35	33.00	46
G27	1HB1	32.85	47
G49	6D12	32.78	48
G26	5H61	32.58	49
G28	2H21	32.42	50
G23	KE22	32.31	51
G67	6C11	32.17	52
G55	5B17	32.15	53
G29	2C20	32.06	54
G21	5C15	31.85	55

Table 7: Continue

G78	1F4	31.76	56
G34	5E+08	31.39	57
G40	6B90	31.37	58
G71	5E+30	31.26	59
G57	1B5	31.22	60
G53	3C21	31.19	61
G16	6H49	31.01	62
G86	6D44	30.88	63
G66	5C44	30.81	64
G81	6GC	30.79	65
G59	6C32	30.76	66
G64	6C25	30.67	67
G73	6H58	30.67	68
G79	1HA1	30.29	69
G68	4E+05	30.20	70
G56	1B14	30.12	71
G54	UK 4	29.94	72
G58	6H22	29.05	73
G60	6C30	28.91	74
G76	1F77	28.90	75
G83	5E+87	28.37	76
G92	1F57	28.31	77
G20	3GA	28.27	78
G72	1H1	28.25	79
G85	6H17	28.08	80
G22	UK5	27.61	81
G41	6C29	27.42	82
G82	6BA	27.26	83
G63	3H1	27.14	84
G19	2AB	27.10	85
G91	6GD	26.97	86
G89	2C21	26.86	87
G96	3H17	26.71	88
G37	5B26	26.67	89
G84	5H1	26.61	90
G87	1HH1	26.50	91
G97	1F11	26.44	92
G90	2C57	26.04	93
G93	3C20	25.81	94
G100	2F19	25.60	95
G88	3F29	25.41	96
G102	6B55	25.24	97
G101	1C48	24.60	98
G103	5F58	24.48	99
G106	6B37	24.46	100
G107	5A2	24.06	101
G98	2GC	24.05	102
G99	1C7	23.45	103
G111	1HK	23.10	104
G95	1G31	23.09	105
G105	4DA	22.14	106
G112	1H11	22.10	107
G109	1C47	21.73	108
G94	2B11	21.70	109
G108	1G35	21.17	110
G110	2H4	20.50	111
G104	1F6	19.29	112

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GGE Biplot Analysis: Winning Genotypes and Mega-Environments

In the GGE analysis, IPCA 1 contributed 66.37% while IPCA 2 accounted for 11.07% of the total variation. The GGE biplot therefore explained 77.45% of the G and G x E interaction variation (Fig. 2). Based on biplot analysis, two mega-environments are suggested. The first mega environment contains environments ENVI 1, ENVI 2, ENVI 4 and ENVI 6 while the second mega environment contains environments ENVI 3 and ENVI 5. Potato clone G6 was the winner in the first mega environment while clones G47 and G52 were the winners in the second mega environment. This means that clone G6 (6CB) is the most specifically suited to the first mega environment and clones G47 and G52 are specifically suited to the second mega environment. Other clones that are specifically suited to the second mega environment are G3, G70, G32, G24 and G48.

The most discriminating environments were ENVI 3 and ENVI 2 (Fig. 3). ENVI 5 was the least discriminating and hence least informative; genotypic differences in ENVI 5 may not be reliable for selection purposes. In addition, ENVI 4, ENVI 6 and ENVI 2 are quite similar; with limited funds, ENVI 4 and ENVI 6 could be dropped.

The ENVI 2 was the closest to ideal environment and therefore the most desirable of the six environments (Fig. 4). It had great discriminating power and was representative of the test environments. ENVI 5 was the least informative. The ENVI 3 did not appear representative of other environments. However, since it had the longest vector, it had the most discriminating power; it was also a unique environment.

Clone G6 (2E87) was closest to the ideal genotype; it was the highest yielding and most stable (Fig. 5). It was followed by clones G47, G3, G48, G24, G70 and G52.

Based on the yield data across the test environments and the suitability for crisping and chipping, 18 potato clones were selected (Table 8). These clones will be subjected to National Performance Trials (NPT) before release of new varieties.

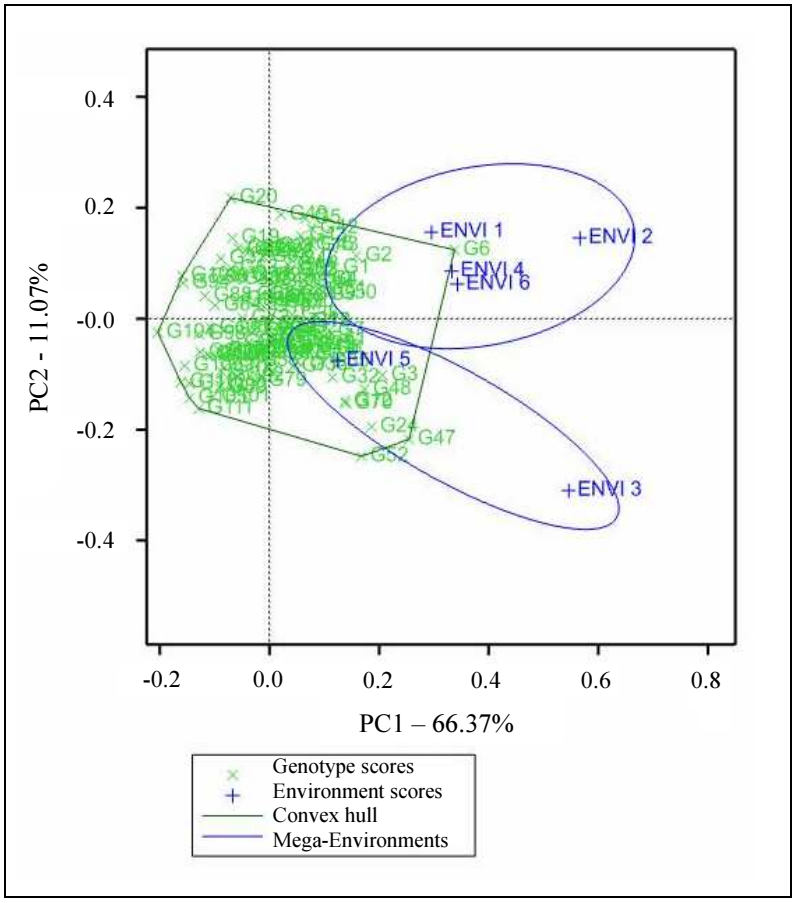

Fig. 2: The which-won-where || view of the GGE biplot under each mega-environment constructed based on environment-centred and symmetrical singular-value partitioning

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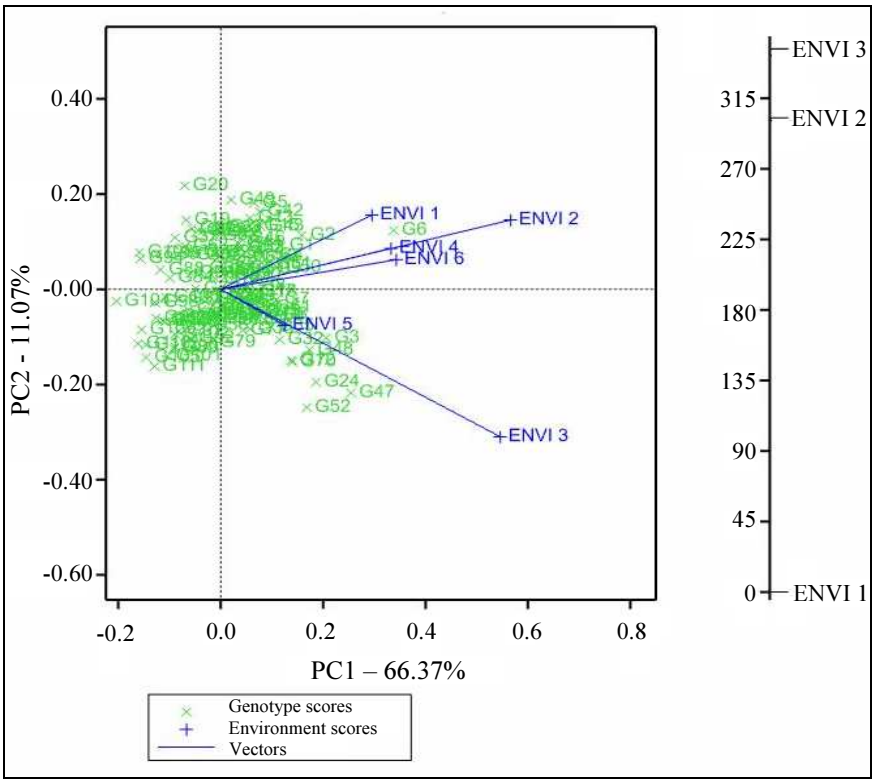

Fig. 3: Vector view of the GGE biplot showing the discriminating power and representativeness of the test environments

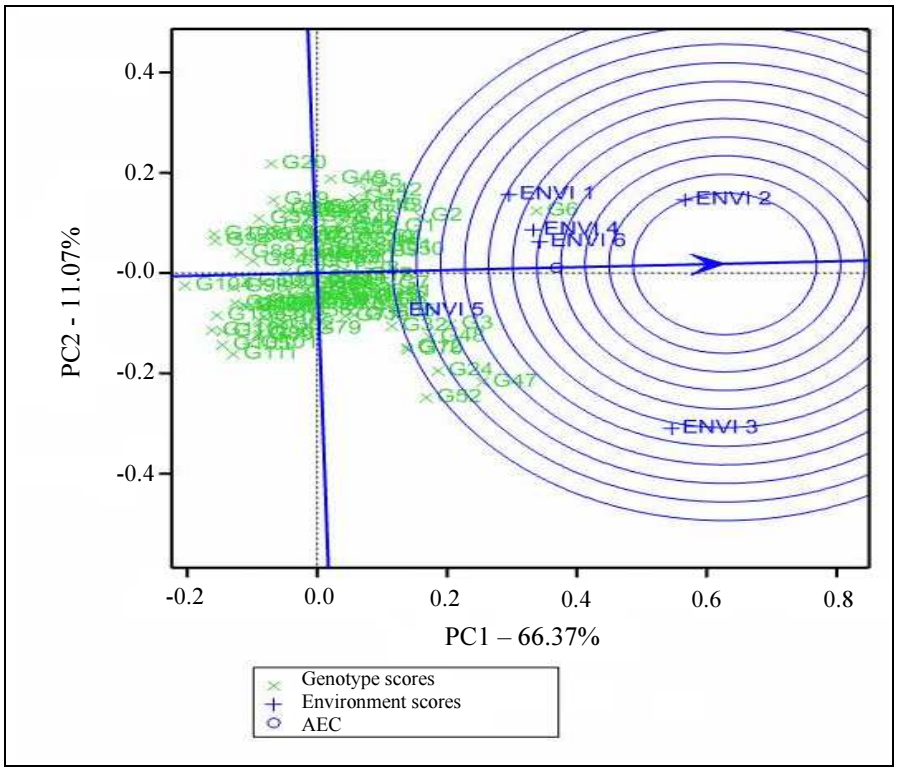

Fig. 4: Biplot for comparison of all environments with the ideal environment constructed based on environment-centred and environment-focused singular-value partitioning

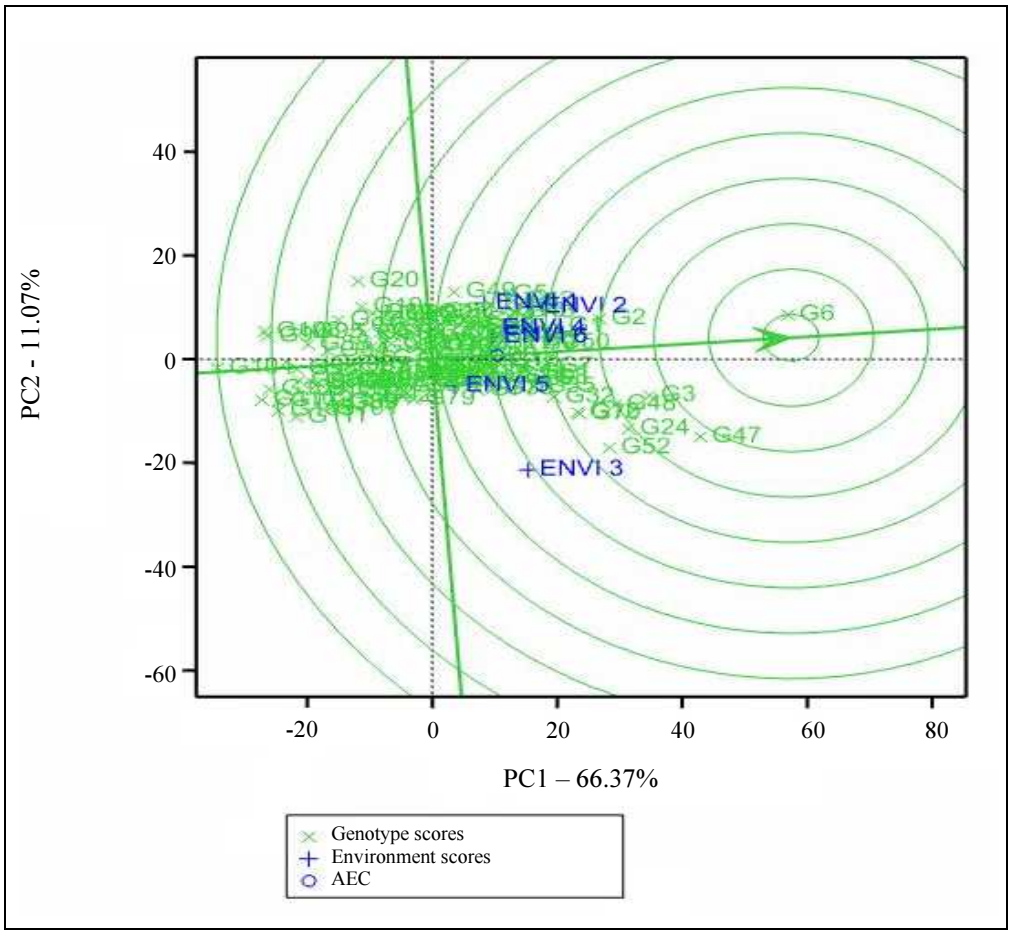

Fig. 5: Biplot showing comparison of all genotypes with ideal genotype constructed based on environment-centred and genotype-focused singular-value partitioning.

Discussion

The paper reports the progress made by the Kenya Agricultural and Livestock Research Organization (KALRO) potato breeding programme at Tigoni, Limuru in re-introducing cross breeding activities to develop new potato varieties. Though new varieties have not been released, promising results have been received so far. The fourth clonal generation had higher mean yield (35.7 ton ha^{-1}) than the third clonal generation (33.1 ton ha^{-1}) possibly due to the higher rainfall which were experienced during the fourth clonal generation or the cooler temperatures or both. Generally, long rains seasons in the Kenyan highlands have higher rainfall and cooler temperatures than the short rains seasons; the trend is also evidenced in the advanced yield trials (Table 6). Consequently, potato being a C_3 cool season crop is likely to benefit more from the cool temperatures (Haverkort *et al*., 1990). Alternatively, it could be due to increase in size of seed tuber planted as clonal generations progressed. Studies have shown an association between the weight of tuber planted and the resulting yield (Brown and Caligari, 1986). Among the five high yielding clones, four of them had CIP clone 394895.7 (E) as the female parent (Table 8). It appears this clone had a high general combining ability for yield. In the stability studies, the clones were ranked differently which indicated crossover GEI (Table 6). This inconsistency in ranking could be due to clone x site, clone x season and clone x site x season interactions. The GEI makes it difficult to recommend a given clone to a specific area. Consequently, more dependable information will be generated when the National Performance Trials (NPT) are done on selected clones. This is because a high yielding generally adapted potato variety would be desirable for production in the major potato growing regions. From the AMMI analysis (Table 5), the first two IPCA's were significant ($p \leq 0.001$) and they accounted for 60.62% of the G x E interaction. This corroborates with previous findings that G x E data sets are best described by AMMI models with one or two multiplicative terms (Gauch and Zobel, 1988).

Table 8: Potato clones selected after advanced yield trials

Clone	Mean yield (t ha^{-1})	Fresh cooking	Crisping	Chipping
2E87	51.81			
4C19	48.1			X
1EY	45.49	X	X	X
1EX	42.98		X	
2E68	42.61			
1F15	42.15			X
1EU	40.84		X	
6B170	40.08		X	
3E03	39.38	X		X
1HG	39.38		X	
5C39	39.31		X	
5E17	39.26			
6D47	38.99		X	
6D10	38.62		X	X
3C22	38.58		X	
1G53	37.02		X	
6D45	36.19		X	
6CB	39.47			

Based on the yield data across the test environments (AYT) and the suitability for crisping and chipping, 18 potato clones were selected (Table 8). Among them, 11 (61.11%) have good crisping quality. These 18 clones were recommended for the National Performance Trials (NPT) before release of new varieties.

Conclusion

From the foregoing, it is likely that KALRO-Tigoni will release high yielding potato varieties soon. I addition, release of new crisping and chipping varieties will be a boost to the local processing sector which is expanding fast.

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Author's Contributions

Jane Muthoni: She designed the project, did all the field work and data collection. She wrote the paper.

Hussein Shimelis: He did data analysis and critically reviewed the paper. He approved the paper to be submitted in the current form.

Ethics

The authors hereby confirm that this manuscript is original work and do not contain any conflict of interest.

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