Potato Research
https://doi.org/10.1007/s11540-024-09790-5

Phenotypic Diversity of Released South African Bred Potato Varieties for Tuber Yield and Processing Quality

Ntombokulunga W. Mbuma[1,3] · Philippus J. Steyn[2] · Sunette M. Laurie[1] · Maryke T. Labuschagne[3] · Michael W. Bairu[1,4]

Received: 13 December 2023 / Accepted: 21 August 2024

Abstract

Potato (*Solanum tuberosum* L.) is a nutritious starchy tuber crop consumed as a staple food in most potato growing countries. Its productivity and production are limited by climate change; thus, it is of utmost importance to tap into the diversity of germplasm resources, therefore, diversifying the potato varieties available for production. The objectives of this study were to determine the phenotypic diversity among the selected Agricultural Research Council-Vegetable, Industrial and Medicinal Plants (ARC-VIMP) potato varieties for tuber yields and processing quality and to determine the correlation between measured traits. Two imported and 22 local potato varieties were planted in three different environments in South Africa. Significant ($P < 0.001$) differences in the tested varieties across all environments were observed for all measured traits. High broad-sense heritability (> 0.6) was observed for most of the traits, except for fry colour and the yield of unmarketable tubers. Nine ARC varieties and three standard varieties were associated with high tuber yield and quality traits, indicating their suitability for the fresh market and processing industry. Variety Mondial and five ARC varieties were associated with high tuber yield, indicating their suitability for the fresh market. Varieties released between 2004 and 2021 had high tuber yield, dry matter and specific gravity compared to the standard varieties and varieties released between 1980 and 1999, although there were slight differences in the magnitudes of their traits measured. These varieties could be recommended for commercial production for specific markets and for use as potential parents for further genetic improvement of the potato crop.

Keywords Adaptability · Crop improvement · Germplasm resources · Processing quality · *Solanum tuberosum* L.

Extended author information available on the last page of the article

Published online: 07 September 2024

Introduction

Potato (*Solanum tuberosum* L.) originated in South America, and it has been cultivated worldwide under diverse environmental conditions ranging from irrigated commercial farms to tropical highland zones; thus, potato can significantly contribute to climate smart agriculture (Koco et al. 2020). Globally, the production of potatoes was estimated at over 376 million metric tons in 2021 (Statista 2022). It is the fourth most important crop for human consumption after rice, maize and wheat (Devaux et al. 2014, 2020), due to its nutrient content. Potato tubers contain starch (70 to 80%), protein (1 to 2% fresh weight; 8 to 9% dry weight), vitamin C, minerals (iron and potassium) and phytochemicals (carotenoids and polyphenols) (Murniece et al. 2014; Hellmann et al. 2021). The potato crop is cultivated mainly for human consumption and to a lesser extent for animal feed and fuel grade ethanol (Memon et al. 2017), and is considered as a food security and cash crop in most growing countries. The contribution of potatoes to the global supply has increased tremendously in the last two decades (Devaux et al. 2020), while the consumption of potato has doubled in the previous decade in developing countries (Mthembu et al. 2022). In South Africa, annual production has been relatively stable at 2.6 million tons over the past 4 years (Department of Agriculture, Land Reform and Rural Development 2022), of which 1.059 million tons (40.3%) were marketed on the National fresh produce markets.

Quality is one of the most important characteristics of potato, and its quality is dependent on external and internal aspects of the tuber (Naumann et al. 2020). Potato dry matter content is an important attribute to both the food and non-food potato industries determining both the quality and yield of the processed product (Scanlon et al. 1999). A dry matter (DM) content above 20% is mostly preferred for processed products (Mehta et al. 2011; Kita 2014). The specific gravity of potato tubers is another important quality criterion for processing potatoes. It is used as an estimate of the solids or dry matter content of tubers (Abong et al. 2009). Specific gravity (SG) is positively correlated with the dry matter content of tubers, and it has been used to measure potato quality due to its repeatability, simplicity and rapid determination (Feltran et al. 2004). The specific gravity has also been considered the most practical index of mealiness. Thus, it is extensively used by industrial processors to assess the suitability of tubers for the production of processed products (Bedini et al. 2023). Fry colour in potatoes is another important trait as it determines the acceptability of fried products. For frying, potato varieties with a high specific gravity and low reducing sugar content are targeted, since these factors influence the colour, texture and oiliness of French fries (Ngobese 2014). A light or light golden-yellow colour is preferred, while a brown or black colour is considered undesirable (Roe et al. 1990; Ezekiel et al. 2003). Nevertheless, the DM, SG and fry colour vary among potato varieties, and this could be attributed to the genotypic effect, environmental conditions and general farming practices (Ngobese 2014). Significant genotype by location, genotype by season and genotype by year interactions for SG and DM have also been reported (Abebe et al. 2013). This highlights the need to assess potato genotypes under varying environmental conditions to determine the suitable environment in which varieties can manifest their maximum performance potential.

The size of tubers and their quantity have a significant influence on the total tuber yields (Aliche et al. 2019). The tuber sizes and quantity are variety specific and could also be influenced by the growing conditions and management practices (Ortiz et al. 2022). Yield is a polygenic trait with small additive genetic effects and is most likely to be influenced by the environmental conditions, resulting in low heritability estimates and instability in the yield performance of varieties (Falconer and Mackay 1996; Lynch and Walsh 1998). Thus, the unstable and unpredictable yield performance of the varieties could potentially lead to poor adoption of the varieties by farmers.

In South Africa, the Department of Agriculture established a potato breeding programme in 1947, and the breeding targets for the period before 1979 were to produce seed with resistance to potato leafroll virus. Since 1979, the breeding programme targets changed to varieties that are high-yielding with good finishing skin and common scab resistance. In the late 1990s, the breeding programme targets changed to varieties with high yield, good processing quality (i.e. high dry matter content), with good skin finishing, resistance to common scab and tolerance to heat. Since the inception (1990s) of the Agricultural Research Council-Vegetable, Industrial and Medicinal Plants (ARC-VIMP) potato breeding programme, 22 potato varieties have been released. Most of these potato varieties were bred and released prior to the year 2000. In general, the ARC potato varieties are characterized by high tuber yield, good processing quality traits and resistance to virus and fungal diseases. However, there is a poor adoption of the ARC potato varieties by small- and large-scale farmers, due to large marketing campaigns for imported varieties. For example, the main varieties sold on the fresh produce markets for the 2018 calendar year were Mondial (54%), Sifra (24%), Lanorma (9%), Valor (3%), Up-To-Date (2%), BP1 (2%), Avalanche (1%), Savana (1%) and others (4%). Changes in climate over the years, recent erratic rainfall, drought and excessive heat experienced quests for the re-evaluation of released South African varieties with a focus on yield potential and processing quality.

The evaluation and characterization of South African potato varieties for tuber yield and processing quality traits are of great importance in identifying varieties with superior yield and processing quality which can be recommended for commercial production. In addition, the interrelationship between the tuber yields and processing quality traits has not been studied in the released South African potato varieties. Understanding relationships between tuber yield and processing quality traits of the existing varieties will provide important information for breeders and guide trait selection during the evaluation of field trials. Hence, the objectives of this study were to determine the phenotypic diversity among the ARC-VIMP selected potato varieties for tuber yield and processing quality traits, and to determine the interrelationship between different tuber yields and processing quality traits.

Materials and Methods

Study Material

The 24 potato varieties included in this study were part of the ARC germplasm collection (Table 1). Twenty-one were bred in South Africa, while three were introduced varieties (Up-to-date, Pentland Dell and Mondial).

Experimental Sites, Design, Establishment and Management

The trials were planted at Cedara in March 2017 and at Roodeplaat in August 2017 and March 2018 (Table 2). The experimental sites represent different environmental conditions.

The trial was planted in a randomized complete block design with three replicates. For each variety, 30 tubers per plot were planted in single rows of 9 m long, at a spacing of 0.5 m between the rows, 0.15 m between the plants within the row and

Table 1 List of the selected ARC and foreign potato varieties used in the study

Variety code	Variety name	Type of market	Year of release
1	ARC-Vanderplank	Standard variety (French fries)	1981
2	ARC-Buffelspoort	Standard variety (table potato)	1981
3	ARC-BP1	Standard variety (table potato)	1980
4	Up-To-Date	Standard variety (table and processing)	1981
63	ARC-Sandvelder	Table and processing	1988
94	ARC-Hoëvelder	Table and processing	1988
205	ARC-Ropedi	Table and processing	1998
227	ARC-Rotharo		1995
282	ARC-Ronn	Table potato	1995
474	ARC-Mnandi	Table potato	1992
712	ARC-Aviva	Crisps	1997
812	ARC-Baroc		1997
866	ARC-Caren	Crisps and French fries	1997
939	Pentland Dell	Imported variety (Table and processing)	1991
975	ARC-Darius	Table and processing	1997
1125	Mondial	Imported variety (table potato)	1993
1153	ARC-Eryn	French fries	1998
1168	ARC-Esco	Table potato	1998
1359	ARC-Fabien	Table and processing	2004
1367	ARC-Frodo	Table and processing	2004
1564	ARC-PT1301	Table and processing	2016
1760	ARC-Freek	Table and processing	2021
1823	ARC-PT1302	Table and processing	2016
1898	ARC-Arno	Table and processing	2021

Table 2 Data of experimental sites and planting and harvesting dates

Location	Province	GPS coordinates	Date of planting	Date of harvesting	Avg annual rainfall (mm)	Altitude (m asl)	Avg min temp (°C)	Avg max temp (°C)
Cedara	KwaZulu-Natal	29.32° S, 30.16° E	15 March 2017	July 2017	900	1053	4.0	25.0
Roodeplaat	Gauteng	25.60° S, 28.34° E	15 August 2017	Jan 2018	584	1168	21.2	38.0
Roodeplaat	Gauteng	25.60° S, 28.34° E	15 March 2018	July 2018	620	1168	21.2	38.0

3 m between the replications. Fertilizer (N:P:K = 2:3:4) was applied before planting as per the field recommendation, which was guided by the soil analysis. Weeding was done before planting and after the planting before emergence using pre-emergence herbicides. Disease inspection and scoring were done throughout the cropping season. Supplemental irrigation was applied by means of sprinklers when the amount of rainfall during the cropping season was not enough for optimal growth and development.

Data Collection

All tubers per variety were classified into different tuber sizes, namely, large (< 200 g), medium (80–199 g), small (50–79 g) and unmarketable (< 50 g or > 1200 g), which were cracked, rotten, insect infested, rat damaged, mechanically damaged, long crooked or sprouted and weighed separately. The number and weight of marketable and unmarketable tubers were determined and used to calculate the total yield per class. The tuber weights per size were used to determine the yield (t ha^{-1}) of the different tuber sizes.

The SG was determined on 15 randomly selected tubers for each replicate per variety from each trial. For SG determination, the 15 selected tubers were weighed in air and also in water. The SG was determined using the following formula (Kumar et al. 2005):

$$SG = \frac{\text{weight air}}{\text{weight air} - \text{weight water}}$$

Dry matter (DM) was expressed as a percentage and calculated from the SG using the following formula (USDA 1997):

$$DM\% = 24.184 + 211.04 * (SG - 1.0988)$$

Dry matter yield (t ha^{-1}) was determined using the following formula:

$$\text{DM yield} = (\text{total yield } \times DM\%)/100$$

Fry colour was determined by taking 2-mm-thick tuber slices from the width of 15 randomly selected medium-sized tubers (80–199 g). The frying of crisps was done in sunflower oil at 180 °C for 3 min using a deep fryer. Crisps were crushed before measuring their colour. The reflected light was measured using a Hunter D25LT Gen 2 calorimeter (HunterLab, Virginia, USA), which allows measurement of the reflectance of coarse, non-homogeneous, irregularly shaped samples like potato chips. It is a 45°/0°, circumferentially illuminated instrument using a faceted spherical reflector to reduce the effect of directional and uneven samples on the measured colour. The light reflected back from the tungsten-halogen light source is focused on photo-detectors to approximate the L, a and b functions. The opponent colour scale gives measurements of colour in units of approximate visual uniformity throughout the colour solid. The Hunter scale L was used to measure the fry colour. Lightness varies from 100 for perfectly white to zero for black. The benchmark used for acceptable fry colour is L > 45. Higher values reflect more light from the fried crisps and are lighter than chips with a lower index values.

Data Analysis

All data were subjected to analysis of variance (ANOVA) using GenStat 22nd version (VSN International, 2022), to determine the effect of genotype and genotype by environment interaction. The least significant difference ($P < 0.05$) was used to separate the means. The potato varieties were considered fixed because their genetic background is unique in the available germplasm collection. The environments were considered random because they represent a random sample of all possible environments representing suitable potato growing conditions in South Africa.

The variance components and H^2 for single trials were calculated using the following formulas (Shimelis and Shiringani 2010):

$$\sigma^2 G = \frac{MS_G - MS_E}{r}$$
$$\sigma^2 E = MS_E$$
$$H^2 = \frac{\sigma^2 G}{\sigma^2 G + \sigma^2 E}$$

The variance components and H^2 across environments were calculated using the following formulas (Shimelis and Shiringani 2010):

$$\sigma^2 G = \frac{MS_G - MS_{GEI}}{re}$$
$$\sigma^2 GE = \frac{MS_{GEI} - MS_E}{r}$$
$$\sigma^2 e = MS_e$$
$$\sigma^2 p = \sigma^2 G + (\sigma^2 GEI/e) + (\sigma^2 E/re)$$
$$H^2 = \frac{\sigma^2 G}{\sigma^2 p}$$

where $\sigma^2 G$ = genotypic variance, $\sigma^2 GE$ = genotype by environment variance interaction, $\sigma^2 E$ = error/residual variance, $\sigma^2 p$ = phenotypic variance, MS_G = mean square of genotype, MS_{GEI} = mean square of genotype by environment interaction, MS_E = mean square error/residual, G = genotypes (fixed), r = replications (random), E = environments (random), and H^2 = broad sense heritability.

Phenotypic correlation analysis was done to determine the association between tuber yields and frying quality and was done using GenStat 22nd version (VSN International, 2022). Principal component analysis and clustered heat maps were done using XLSTAT software version 2022.3.2 (Addinsoft 2022).

Results

Analysis of Variance, Broad-Sense Heritability and Variety Mean Performance

The genotype, environment and their interaction effects were highly ($P < 0.001$) significant for all measured traits (Table 3). The genotypic variance was larger than the

Table 3 Mean squares, variance components (σ^2) and broad-sense heritability (H^2) for potato tuber yields and quality traits

Stats	DF	DM	DM yield	Fry colour	SG	Total yield	Yield large	Yield medium	Yield small	Yield unmarketable
Rep	2	9.35	4.21	81.64	0.00021	135.57	38.11	30.22	0.14	5.52
Genotype (*G*)	23	17.73***	14.65***	27.78***	0.00040***	312.46***	203.86***	65.95***	8.03***	21.42***
Environment (*E*)	2	13.16***	69.77***	1359.82***	0.00030***	2067.32***	2396.36***	749.50***	32.07***	1022.19***
GEI	46	4.96***	5.03***	19.18**	0.00011***	122.32***	70.01***	46.55***	5.53***	19.54***
Residual	142	1.54	1.53	10.29	0.00003	32.96	14.54	8.28	0.95	3.07
$\sigma^2 G$		12.77	9.62	8.60	0.00029	190.14	133.85	19.40	2.50	1.88
$\sigma^2 GEI$		1.14	1.17	2.96	0.00003	29.79	18.49	12.76	1.53	5.49
$\sigma^2 E$		1.54	1.53	10.29	0.00003	32.96	14.54	8.28	0.95	3.07
$\sigma^2 P$		14.69	11.54	19.88	0.00033	233.03	154.55	31.93	3.96	6.78
H^2		0.87	0.83	0.43	0.87	0.82	0.87	0.61	0.63	0.28
Grand mean		20.48	6.70	48.04	1.08	32.81	12.20	13.37	3.44	3.79

GEI genotype by environment interaction, *DM* dry matter, *SG* specific gravity, *DF* degrees of freedom

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$

GEI variance. However, the phenotypic variance was higher than the genotypic variance for all traits. The H^2 estimates ranged from 0.28 to 0.87 among the measured traits. Fry colour and yield of unmarketable tubers had low H^2 (<0.05) estimates, while the other traits had H^2 estimates above 0.6.

The mean values for DM ranged from 18.3 to 23.2% (Table 4). Varieties ARC-Aviva, ARC-Caren, Pentland Dell, ARC-Hoëvelder, ARC-Darius, ARC-Ropedi, ARC-Fabien, ARC-Frodo, ARC-PT1301, ARC-Freek, ARC-PT1302, ARC-Arno and ARC-Eryn had DM values above 20%. The mean DM yield over the three locations ranged from 4.15 to 9.09 t ha^{-1} (Table 4). Promising DM yields were recorded for varieties MONDIAL, ARC-PT1301, ARC-Freek, ARC-PT1302, ARC-Arno, ARC-Buffelspoort, ARC-Ronn, ARC-BP1, ARC-Sandvelder, ARC-Aviva, ARC-Caren and ARC-Darius.

The quality parameter fry colour ranged from 45.2 to 51.8% (Table 4); therefore, all varieties showed acceptable colour, while SG means ranged from 1.0710 to 1.0930. Mean values for yield parameters were 21.26 to 43.29 t ha^{-1} for total yield, 5.48 to 25.18 t ha^{-1} for the yield of large tubers, 7.69 to 19.23 t ha^{-1} for the yield of medium tubers, 2.04 to 5.37 t ha^{-1} for the yield of small tubers and 1.55 to 8.89 t ha^{-1} for unmarketable tubers. Total tuber yields were above the mean for ARC-Eryn, ARC-PT1301, ARC-Freek, ARC-PT1302, ARC-Arno, ARC-Buffelspoort, ARC-Ronn, ARC-Mnandi, ARC-Sandvelder and ARC-Caren. Figure 1 shows that varieties that were released between 2004 and 2021 had a higher DM, DM yield, SG, yield of medium tuber size and total tuber yield compared to the standard varieties and varieties released between 1980 and 1990.

Phenotypic Correlations of All Measured Traits

Table 5 indicates highly significant ($P<0.0001$) and positive correlations ($r=0.42$) between DM with DM yield ($r=0.42$), fry colour ($r=0.40$), SG ($r=1.00$), yield of medium tubers ($r=0.41$) and yield of unmarketable tubers. There were significant ($P<0.05$) and negative correlations between DM and yield of large tubers ($r=-0.34$). There were highly significant and positive correlations between DM yield with SG ($r=0.42$), tuber yield ($r=0.92$), yield of large tubers ($r=0.75$), yield of medium tubers ($r=0.65$) and yield of small tubers ($r=0.23$). There were highly significant ($P<0.001$) and positive correlations for fry colour with SG ($r=0.40$) and significant positive correlations ($P<0.01$) for fry colour with the yield of medium tubers ($r=0.19$).

Principal Component Analysis

To visualize the performance of varieties and their associated traits, the data was subjected to PCA. The first three PCs of the PCA accounted for 82.8% of the total variation in the dataset and had eigenvalues of equal to or greater than one (Table 6). PC1, PC2 and PC3 explained 41%, 26.6% and 15.2% of the total variation, respectively. Only PC1 and PC2 were interpreted because they explained most of the variation in the dataset. The DM, DM yield, fry colour, SG, total yield and yields of

Table 4 Performance of varieties based on the mean values for all traits in three environments

Variety	DM %	DM yield t ha^{-1}	Fry colour	SG	Total yield t ha^{-1}	Yield large	Yield medium	Yield small	Yield unmarketable
ARC-Arno	22.83fg	7.91efg	45.71ab	1.0924fg	34.90cdefgh	13.39bcdef	15.21bcdef	2.61ab	3.69abcd
ARC-Aviva	23.15g	7.12cdefg	51.81c	1.0939g	30.82abcdef	8.96abc	14.88bcdef	4.04bcde	2.95abc
ARC-Baroc	19.16abc	4.15a	47.29abc	1.075abc	21.26a	6.69a	7.69a	2.86abc	4.03abcd
ARC-Caren	21.05cdefg	8.38 fg	48.43abc	1.084cdefg	39.87fgh	17.87ef	14.99bcdef	3.62abcd	3.38abcd
ARC-Darius	22.01defg	6.84cdef	49.80abc	1.0885defg	31.1abcdefg	10.70abcd	12.40abc	3.01abc	5.00bcd
ARC-Eryn	21.05cdefg	5.96abcde	50.29abc	1.084cdefg	28.55abcd	9.21abc	12.41abc	2.46ab	4.47abcd
ARC-Esco	19.61abc	5.38abc	47.86abc	1.0771abc	27.37abc	11.25abcde	11.41abc	2.21a	2.50ab
ARC-Fabien	20.77bcdef	6.05abcde	45.78ab	1.0826bcdef	29.09abcde	10.03abcd	12.77bcd	2.97abc	3.32abcd
ARC-Freek	22.24defg	8.41fg	49.13abc	1.0896defg	38.07defgh	8.97abc	19.23f	5.37e	4.51abcd
ARC-Frodo	20.57bcde	6.39bcdef	46.02ab	1.0817bcde	31.48bcdefg	14.47bcdef	12.13abc	2.5ab	2.38ab
ARC-Hoëvelder	20.88cdef	5.93abcde	46.30abc	1.0832cdef	28.90abcde	8.17ab	12.72bcd	3.16abc	4.86bcd
ARC-Mnandi	19.68abc	6.49bcdef	48.06abc	1.0775abc	32.92bcdefg	8.09ab	14.05bcde	5.05de	5.74 cd
ARC-PT1301	21.17cdefg	8.01efg	50.86bc	1.0845cdefg	38.54defgh	14.52bcdef	18.46ef	3.22abc	2.34ab
ARC-PT1302	22.46efg	9.09g	47.19abc	1.0906efg	40.71fgh	10.93abcd	15.76cdef	5.13de	8.89e
ARC-Ronn	19.58abc	7.87efg	47.44abc	1.077abc	40.55fgh	15.46cdef	15.35bcdef	3.59abcd	6.15de
ARC-Ropedi	20.22abcd	6.42bcdef	48.47abc	1.080abc	31.37bcdefg	9.83abcd	14.35bcdef	4.01bcde	3.18abcd
ARC-Rotharo	18.35a	4.48ab	45.23a	1.0712a	24.19ab	5.51a	10.74ab	4.36cde	3.58abcd
ARC-Sandvelder	18.32a	7.85efg	45.54ab	1.0710a	43.29h	18.84fg	17.7def	4.03bcde	2.73abc
BP1	21.01cdefg	6.97cdefg	49.48abc	1.0838cdefg	32.59bcdefg	14.23bcdef	11.3abc	3.94bcde	3.12abcd
ARC-Buffelspoort	19.10abc	6.74cdef	47.16abc	1.0747abc	35.37cdefgh	18.07f	11.19abc	2.74abc	3.36abcd
Mondial	18.65ab	7.62defg	49.18abc	1.0726ab	40.95gh	25.18g	10.92abc	2.04a	2.81abc
Pentland Dell	21.08cdefg	5.13abc	48.44abc	1.0841cdefg	24.35ab	5.48a	11.45abc	3.95bcde	3.47abcd
Up-To-Date	19.52abc	5.68abcd	48.28abc	1.0767abc	29.58abcde	10.91abcd	12.11abc	3.58abcd	2.98abc

Table 4 (continued)

Variety	DM %	DM yield t ha^{-1}	Fry colour	SG	Total yield t ha^{-1}	Yield large	Yield medium	Yield small	Yield unmarketable
ARC-Vanderplank	19.11abc	6.00abcde	49.21abc	1.0748abc	31.57bcdefg	16.06def	11.76abc	2.21a	1.55a
Mean (Cedara-2017)	20.84	6.60	43.07	1.0830	13.64	18.48	9.67	2.90	0.60
Mean (Roodeplaat-2017)	20.01	7.74	51.15	1.0790	38.65	10.98	15.53	4.19	7.95
Mean (Roodeplaat-2018)	20.60	5.77	49.89	1.0818	28.13	7.13	14.93	3.34	2.83
Grand mean	20.48	6.70	48.04	1.08	32.81	12.20	13.37	3.44	3.79
LSD	1.58	1.15	2.99	0.003	5.35	3.55	2.68	0.91	1.63

DM dry matter, *LSD* least significant difference, *SG* specific gravity, numbers followed by different letters indicate significant differences between values

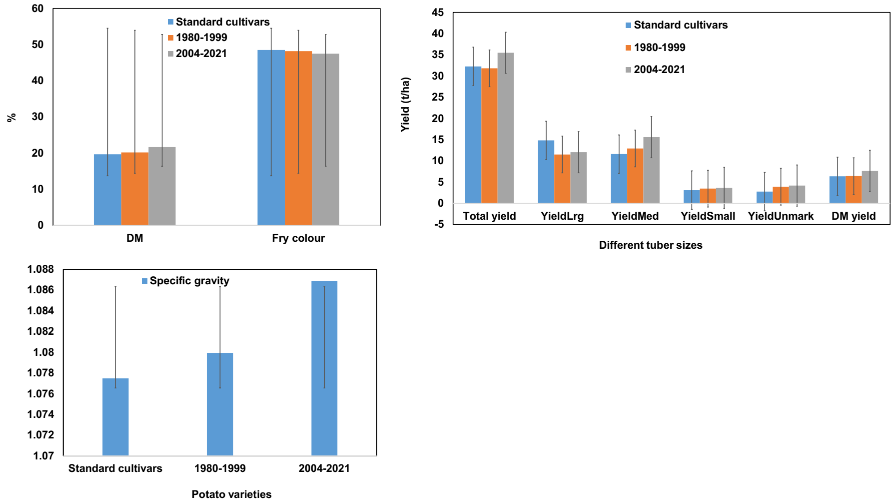

Fig. 1 The performance of potato variety standard varieties, and for varieties released between 1980–1999 and 2004–2021 for all measured traits. The vertical bars are standard error bars

all different tuber sizes contributed positive values to the PC1. However, all traits contributed values below average (<0.5) in PC1. PC2 was strongly and positively influenced by yield of medium tubers. The DM yield, total yield, yield of large and medium tubers contributed below average positive values to PC2.

The PCA biplot was used to visualize the performance of the varieties and their associated characteristics (Fig. 2). The PC1 and PC2 explained 67.6% of the total variation. Variety ARC-Sandvelder was associated with the yield of large tubers. Varieties ARC-Caren, ARC-PT1301 and ARC-Ronn were associated with total yield, DM yield and the yield of medium tubers. Varieties ARC-Arno, ARC-Freek and ARC-PT1302 were associated with good fry colour and the yield of medium tubers. Varieties ARC-Mnandi, ARC-Darius and ARC-AVIVA were associated with DM, SG and the yield of small and unmarketable tubers. The PCA showed positive correlations between the total yield, DM yield and the yield of large and medium tubers. The fry colour, DM, SG and the yield of small tubers and unmarketable tubers were positively correlated with each other.

Clustered Heat Map

Cluster I of varieties ARC-Hoëvelder, ARC-Rotharo, ARC-Mnandi and ARC-Baroc was associated with strong positive values for the yield of small and unmarketable tubers and was associated with strong negative values of DM, SG, DM yield, total yield, fry colour and the yield of medium and large tubers (Fig. 3). Cluster II of varieties ARC-Eryn, ARC-Darius, ARC-Esco, ARC-Freek, ARC-Ropedi, ARC-Aviva, Pentland Dell, BP1 and Up-to-Date was associated with strong positive values of DM, SG, the yield of small tubers and fry colour, and associated with negative

Table 5 Phenotypic correlations of all measured traits

	DM	DM yield	Fry colour	SG	Total yield	Yield large	Yield medium	Yield small	Yield unmark
DM	1								
DM yield	0.42***	1							
Fry colour	0.40***	0.09	1						
SG	1.00***	0.42***	0.40***	1					
Yield	0.03	0.92***	−0.07	0.03	1				
Yield large	−0.14*	0.75***	−0.19	−0.14	0.88	1			
Yield medium	0.41***	0.65***	0.19**	0.41*	0.55***	0.10	1		
Yield small	0.10	0.23***	0.24	0.10***	0.22**	−0.18	0.60***	1	
Yield unmark	−0.34***	0.07	−0.10	−0.34***	0.26***	0.08	0.20*	0.50***	1

DM dry matter, *SG* specific gravity

*$P<0.05$; **$P<0.01$; ***$P<0.001$; values without asterisks are non-significant

Table 6 Principal component (PC) analysis eigenvectors for all measured traits in potato varieties

Traits	PC1	PC2	PC3	PC4	PC5
DM	0.36	−0.31	0.36	−0.31	−0.16
DM yield	0.46	0.28	0.00	−0.11	0.04
Fry colour	0.14	−0.04	0.64	0.50	0.54
SG	0.39	−0.33	0.23	−0.29	−0.14
Yield	0.37	0.45	−0.13	0.00	0.09
Yield large	0.06	0.62	0.11	−0.18	0.15
Yield medium	0.44	0.11	−0.07	0.30	−0.45
Yield small	0.29	−0.25	−0.43	0.58	0.02
Yield unmarketable	0.26	−0.24	−0.44	−0.33	0.65
Eigenvalue	3.69	2.40	1.37	0.73	0.58
Variability (%)	40.95	26.63	15.22	8.08	6.42
Cumulative %	40.95	67.58	82.80	90.87	97.29

DM dry matter, *SG* specific gravity

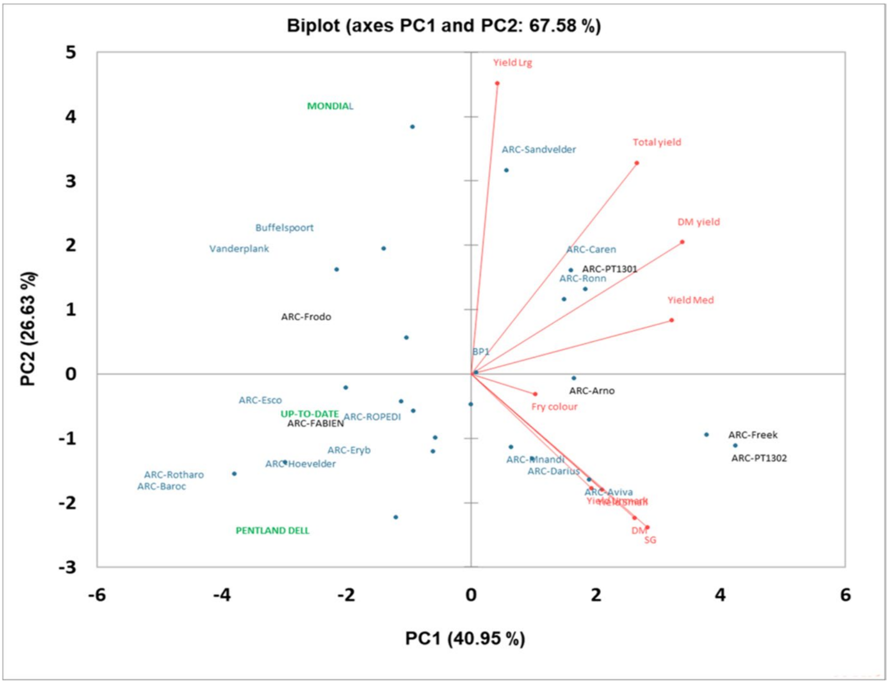

Fig. 2 Principal component (PC) analysis biplot representing potato varieties with their associated traits. Colours: Red = traits, Green = imported varieties, Blue = ARC varieties released 1980–1999, Black = ARC varieties released from 2004 to 2021, DM dry matter, SG specific gravity

values of DM yield, total yield and the yield of medium tubers. Cluster III of varieties ARC-PT1302, ARC-FABIEN, ARC-ARNO and ARC-FRODO was associated with positive values of DM, SG, DM yield, total yield and the yield of medium and

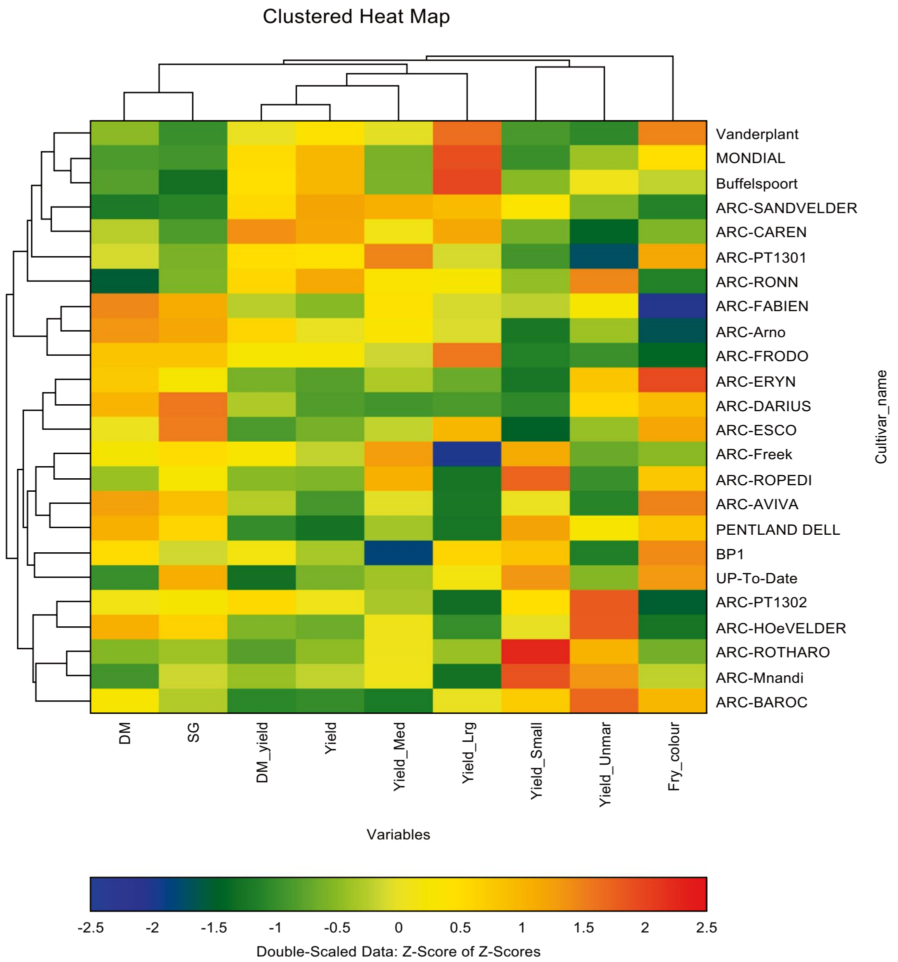

Fig. 3 Clustered heat maps showing potato varieties grouped based on their trait similarities. DM dry matter, SG specific gravity

unmarketable tubers, and negatively associated with the yield of small tubers and fry colour. The cluster IV of varieties Vanderplank, Mondial, Buffelspoort, ARC-Sandvelder, ARC-Caren, ARC-PT1301 and ARC-Ronn was associated with positive values of DM yield, total yield and the yield of medium and large tubers, and negatively associated with DM, SG, the yield of small and unmarketable tubers and fry colour.

Discussion

The significant genotypic effects for all traits indicated the presence of variation among potato varieties, suggesting that superior varieties could be identified, selected and recommended for commercial evaluation. The differences among the varieties could also be attributed to the genetic background of the parents used to develop the varieties (Tessema et al. 2020). Similar findings were also observed among potato varieties for tuber yield in Ethiopia (Wassu 2017; Tessema et al. 2022). Previous studies reported a statistically significant effect of varieties on tuber specific gravity (Berhanu and Tewodros 2016). Significant genotype by environment interaction (GEI) for all traits indicated that the potato varieties performed differently across the test environments. The differences in the performance of potato varieties across environments also indicate that the environment had a large influence on the phenotypic expression of varieties for the measured traits. The significant GEI also indicates that there is a need for potato varieties to be evaluated in several locations and over a number of seasons in order to quantify their adaptation and stability. A previous study has reported significant environmental effect on potato total tuber yield and plant height (Kwambai et al. 2024). Tessema et al. (2020) also reported significant GEI for tuber yield and late blight resistance in Ethiopia, but non-significant GEI for days to flowering, SG and DM. In contrast, Tesfaye et al. (2012) reported a significant effect of GEI effects on DM, starch content and starch yield. Breeding for high-yielding, well-adapted and stable varieties is important for potato production and sustainability.

There was a larger genotypic variance compared to the environment variance for all traits, which resulted in higher H^2 estimates (above 0.6) for most of the measured characteristics, except for fry colour and the yield of unmarketable tubers. Higher H^2 estimates indicate that the phenotypic expression of the potato varieties was mainly due to the genotypic variance and has a high possibility of improvement through selection (Falconer and Mackay 1996; Lynch and Walsh 1998; Visscher et al. 2008). Thus, high H^2 estimates for these traits could indicate high precision and selection efficiency in potato varieties. A previous study (Tessema et al. 2022) investigated the genetic variability among 20 potato varieties in central Ethiopia and reported H^2 estimates that ranged from 0.33 to 0.98 for tuber yield and yield attributes. Low H^2 estimates (below 0.5) for fry colour and the yield of unmarketable tubers indicated that the phenotypic expression of potato varieties for these traits was mainly due to environmental factors. Thus, low H^2 estimates for these traits could indicate a low possibility for improvement of potato varieties through selection. Previous studies have suggested the use of the best linear unbiased predictors to evaluate the performance of potato varieties for low heritability traits to increase the selection efficiency (Slater et al. 2014a, b). Further studies are warranted to investigate the underlying factors that contribute to the environmental variance of these traits and to identify potential strategies for their improvement.

The results from the present study showed that varieties that were released between 2004 and 2021 had a higher DM, DM yield, SG, yields of medium tubers and total tuber yield compared to the standard varieties and varieties released between 1980 and 1990, which indicated that the recently released varieties could be suitable for dual purposes (table and processing). However, there was a slight difference in the magnitudes of all traits measured between the standard varieties, and the varieties released between 1980 and 1999 and between 2004 and 2021. The results indicate that there is a need for newly developed and improved potato varieties with high tuber yields. A previous study reported that varieties had higher yields compared to standard varieties under multiple environments in Bangladesh

(Kundu et al. 2020). For processing, the DM of potato tubers and SG should be above 20% and 1.08, respectively (Marwaha et al. 2010). The DM and SG reported in the current study were higher than 20% and 1.08, respectively, for varieties released between 2004 and 2021 compared to the standard varieties and varieties released between 1980 and 1990. The results suggest that good progress was made in the development of improved varieties for processing quality which could be attributed to the dynamic market demands and that contributes to food security.

Superior potato varieties for DM (ARC-Aviva, ARC-Caren, Pentland Dell, ARC-Hoëvelder, ARC-Darius, ARC-Ropedi, ARC-Fabien, ARC-Frodo, ARC-PT1301, ARC-Freek, ARC-PT1302, ARC-Arno and ARC-Eryn), DM yield (ARC-PT1302), fry colour (ARC-Aviva), SG (ARC-Arno, ARC-PT1302, ARC-Freek, ARC-Darius and ARC-Aviva), total yield (ARC-Sandvelder), yield of large tubers (MondiaL, ARC-Vanderplank, ARC-Frodo, ARC-PT1301, ARC-ARNO, ARC-Buffelspoort, ARC-Ronn and BP1), yield of medium tubers (ARC-Freek), yield of small tubers (ARC-Freek) and low yield of the unmarketable tubers (ARC-Vanderplank) were identified. The identified superior potato varieties could be further evaluated for adaptability and stability in the main potato growing areas in South Africa. The potato varieties that are superior for DM, DM yield, fry colour and SG could be recommended for the fresh and processing markets. According to Mehta et al. (2011) and Ngobese (2014), DM content is the main decisive attribute for processing quality. High DM (above 20%) and SG (above 1.08) are preferable for processing quality, since it allow for improved textural quality of crisps and fries (Rachappanavar et al. 2023), while varieties with low DM, fry colour and SG, but with high yields, could be considered for the fresh market. There is also a need for further evaluation of the superior varieties for resistance to potato virus diseases, as well as tolerance to drought, heat and waterlogging.

Significant and positive correlations among the yields of all different tuber sizes with total yield and dry matter yield indicated that an increase in the number of tubers of any size will have a positive impact on the total yield. Ideally, the potato breeders would want to increase the yield of all different tuber sizes, except the unmarketable potatoes which will have no value in the market. Thus, there is a need for a study to evaluate the factors contributing to unmarketable tubers so that recommendations can be made on how those factors could be reduced. Previous studies (Khayatnezhad et al. 2011; Gashaw and Mohammed 2020) reported significant positive correlations between tuber yield and DM in drought tolerant potato varieties in North-Western Ethiopia. Significant positive correlations between SG, cook colour, DM, DM yield and fry colour indicated that these traits could be improved and selected for simultaneously. The results also indicated that there is a possibility of indirect selection of these traits since an increase in one trait will have a positive influence on others. In contrast, previous studies (Cunningham and Stevenson 1963) reported low correlations between SG and potato chip colour. Significant and positive correlations between DM, DM yield, and fry colour with the yield of medium tubers indicated that an increase in one of these traits will have a positive influence on the improvement and selection of the other traits.

Potato varieties ARC-Caren, ARC-PT1301 and ARC-Ronn were associated with high total tuber yield, DM yield and the yield of medium tubers, suggesting that such genotypes could be used in a breeding programme as parental lines for the development of high-yielding varieties. Potato varieties ARC-Arno, ARC-Freek and ARC-PT1302 were associated with fry colour and the yield of medium tubers, indicating that these varieties could be recommended for the frozen fries market. The potato growers and processing industry would benefit the most from varieties with good high fry or chip quality, SG, DM and high yield. Potato varieties ARC-Mnandi, ARC-Darius and ARC-Aviva were strongly associated with DM, SG, the yield of small tubers and unmarketable yield, indicating that these varieties could be suitable for the table market and as canned potatoes. Potato variety ARC-Sandvelder was associated with the yield of large tubers, and it was also identified as a high-yielding genotype. Thus, variety ARC-Sandvelder should be further evaluated for adaptability and stability in the main potato growing regions of South Africa before the recommendation for commercial release and production.

The cluster II of varieties ARC-Eryn, ARC-Darius, ARC-Esco, ARC-Freek, ARC-Ropedi, ARC-Aviva, ARC-BP1, Pentland Dell and Up-to-date was associated with strong positive values of DM, SG, yield of small tubers and fry colour, and was associated with negative values of DM yield, total yield and the yield of medium tubers. Potato varieties in cluster II would be suitable for the fresh market, and for the processing (crisp) and French fries industry. The cluster III of varieties ARC-PT1302, ARC-Fabien, ARC-Arno and ARC-Frodo was associated with positive values of DM, SG, DM yield, total yield and the yield of medium and unmarketable tubers, and negatively associated with the yield of small tubers and fry colour. The varieties in cluster III would be suitable for the fresh market and processing industry. The cluster IV of varieties ARC-Vanderplank, Mondial, ARC-Buffelspoort, ARC-Sandvelder, ARC-Caren, ARC-PT1301 and ARC-Ronn was associated with positive values of DM yield, total yield and the yield of medium and large tubers, and negatively associated with DM, SG, the yields of small and unmarketable tubers and fry colour, suggesting that these varieties would be most suitable for the fresh market.

Conclusions

The findings showed variation among the ARC potato varieties for most of the traits. The environment significantly influences the performance of potato varieties for tuber yield and processing traits; hence, it is important to evaluate the potential varieties in multiple environments before recommendations are made for commercial production. Newly released varieties outperformed the varieties released between 1980 and 1999 and the standard varieties for tuber yield, DM and SG. However, there was a slight difference in the magnitudes of all traits measured between the standard varieties, and varieties released between 1980 and 1999, and between 2004 and 2021. Varieties ARC-Eryn, ARC-Darius, ARC-Esco, ARC-Freek, ARC-Ropedi, ARC-Aviva, Pentland Dell, BP1, Up-To-Date, ARC-PT1302, ARC-Fabien, ARC-Arno and ARC-Frodo were associated with high tuber yield and processing quality traits, indicating their suitability for the fresh market and processing industry. Varieties ARC-Vanderplank, Mondial, ARC-Buffelspoort, ARC-Sandvelder, ARC-Caren, ARC-PT1301 and ARC-Ronn were associated with high yields, indicating their suitability for the fresh market. These varieties can provide better yield, good processing quality and better adaptability to different climates and soil conditions. The identified superior potato varieties that are well performing and stable can result in increased food security at the national and international level.

Author Contribution Ntombokulunga W. Mbuma: conceptualization; investigation; data curating; methodology; writing—original draft and review and editing. Philippus J. Steyn: conceptualization; project administration; funding acquisition; investigation; resources; review and editing. Sunette M. Laurie: supervision; resources; review and editing. Maryke T. Labuschagne: methodology; supervision; review and editing. Michael W. Bairu: supervision; resources; review and editing.

Funding Open access funding provided by University of the Free State. The research project was funded by the Agricultural Research Council Vegetable, Industrial and Medicinal Plants Institute in South Africa.

Data Availability The data that support the findings of this study are available from the corresponding author, NW Mbuma, upon reasonable request.

Declarations

Ethics Approval and Consent Not required.

Consent for Publication Not required.

Competing Interests The authors declare no competing interests.

References

Abebe TM, Wongchaochant S, Taychasinpitak T (2013) Evaluation of specific gravity of potato varieties in Ethiopia as a criterion for determining processing quality. Kasetsart J - Nat Sci 47:30–41

Abong GO, Okoth MW, Karuri EG, Kabira JN, Mathooko FM (2009) Levels of reducing sugars in eight Kenyan potato cultivars as influenced by stage of maturity and storage conditions. J Anim and Plant Sci 2:76–84

Aliche EB, Oortwijn M, Theeuwen TPJM, Bachem CWB, van Eck HJ, Visser RGF, van der Linden CG (2019) Genetic mapping of tuber size distribution and marketable tuber yield under drought stress in potatoes. Euphytica 215:186. https://doi.org/10.1007/s10681-019-2508-0

Bedini G, Nallan Chakravartula SS, Nardella M, Bandiera A, Massantini R, Moscetti R (2023) Prediction of potato dry matter content by FT-NIR spectroscopy: impact of tuber tissue on model performance. Futur Foods 8:100241. https://doi.org/10.1016/j.fufo.2023.100241

Berhanu B, Tewodros M (2016) Performance evaluation of released and farmers' potato (*Solanum tuberosum* L.) varieties in eastern Ethiopia. Sky J Agric Res 5:034–041

Cunningham CE, Stevenson FJ (1963) Inheritance of factors affecting potato chip color and their association with specific gravity. Am Potato J 40:253–265. https://doi.org/10.1007/BF02850325

Department of Agriculture, Land Reform and Rural Development (DALRRD) (2022) Abstracts of Agricultural Statistics, Directorate Statistics and Economic analysis. pp. 1–112. http://www.dalrrd.gov.za/phocadownloadpap/Statistics_and_Economic_Analysis/Statistical_Information/Abstract%202022.pdf. Accessed 10 March 2023

Devaux A, Kromann P, Ortiz O (2014) Potatoes for sustainable global food security. Potato Res 57:185–199. https://doi.org/10.1007/s11540-014-9265-1

Devaux A, Goffart JP, Petsakos A, Kronmann P, Gatto M, Okello J, Suarez V, Hareau G (2020) Global food security, contributions from sustainable potato agri-food systems. In: Campos H, Ortiz O (eds) The potato crop. Springer, Cham. https://doi.org/10.1007/978-3-030-28683-5_1

Ezekiel R, Singh B, Kumar D (2003) A reference chart for potato chip colour for use in India. J Indian Potato Assoc 30:259–265

Falconer DS, Mackay TF (1996) Introduction to quantitative genetics, 4th edn. Longman, Essex

Feltran JC, Lemos LB, Vieites RL (2004) Technological quality and utilization of potato tubers. Sci Agric 61:593–597. https://doi.org/10.1590/S0103-90162004000600006

Gashaw B, Mohammed W (2020) Preliminary analysis of genotypic and phenotypic correlation of traits in drought tolerant potato under moisture deficit areas of North-Western Ethiopia. Potato J 47:9–21

Hellmann H, Goyer A, Navarre DA (2021) Antioxidants in potatoes: a functional view on one of the major food crops worldwide. Molecules 26:2446. https://doi.org/10.3390/molecules26092446

Khayatnezhad MR, Shahriari BR, Gholamin RG, Jamaati-e-Somarin S, Zabihi-e-Mahmoodabad R (2011) Correlation and path analysis between yield and yield components in potato (*Solanum tuberosum* L.). J Sci Res 7:17–21

Kita A (2014) The effect of frying on fat uptake and texture of fried potato products. Eur J Lipid Sci Technol 116:735–740. https://doi.org/10.1002/ejlt.201300276

Koco Š, Vilček J, Torma S, Michaeli E, Solár V (2020) Optimising potato (Solanum tuberosum L.) cultivation by selection of proper soils. Agriculture 10:155. https://doi.org/10.3390/agriculture10050155

Kumar D, Ezekiel R, Singh B, Ahmed I (2005) Conversion table for specific gravity, dry matter and starch content from under water weight of potatoes grown in north-Indian plains. Potato J 32:79–84

Kundu B, Kawochar M, Naznin S, Ahmed N, Halder S, Mostofa M, Delowar H (2020) Stability analysis for yield of Advanced potato genotypes for commercial cultivation in Bangladesh. SAARC J Agric 18(1):73–86. https://doi.org/10.3329/sja.v18i1.48383

Kwambai TK, Struik PC, Gorman M et al (2024) Understanding genotype × environment interactions in potato production to guide variety adoption and future breeding strategies. Potato Res 67:663–694. https://doi.org/10.1007/s11540-023-09650-8

Lynch M, Walsh B (1998) Genetics and analysis of quantitative traits. Sinauer Associates, Sunderland, MA

Marwaha RS, Pandey SK, Kumar D, Singh SV, Kumar P (2010) Potato processing scenario in India: Industrial constraints, future projections, challenges ahead and remedies - A review. J Food Sci Technol 47:137–56. https://doi.org/10.1007/s13197-010-0026-0

Mehta A, Charaya P, Singh BP (2011) French fry quality of potato varieties: effect of tuber maturity and skin curing. Potato J 38:130–136

Memon AA, Shah FA, Kumar N (2017) Bioethanol production from waste potatoes as a sustainable waste-to-energy resource via enzymatic hydrolysis. IOP Conf Ser Earth Environ Sci 73:012003. https://doi.org/10.1088/1755-1315/73/1/012003

Mthembu SG, Magwaza LS, Mditshwa A, Odindo A (2022) Evaluating drought tolerance of potato genotypes at different growth stages using yield performance and tuber quality traits. Sci Hortic 293:110689. https://doi.org/10.1016/j.scienta.2021.110689

Murniece I, Tomsone L, Skrabule I, Vaivode A (2014) Carotenoids and total phenolic content in potatoes with different flesh colour. FoodBalt Proc 2014:206–211

Naumann M, Koch M, Thiel H, Gransee A, Pawelzik E (2020) The importance of nutrient management for potato production Part II: plant nutrition and tuber quality. Potato Res 63:121–137. https://doi.org/10.1007/s11540-019-09430-3

Ngobese NZ (2014) Characterisation of potato varieties recently released in South Africa for frozen French fries. Thesis, University of KwaZulu-Natal

Ortiz R, Reslow F, Cuevas J, Crossa J (2022) Genetic gains in potato breeding as measured by field testing of varietys released during the last 200 years in the Nordic Region of Europe. J Agric Sci 160:310–316. https://doi.org/10.1017/S002185962200034X

Rachappanavar V, Kumar M, Kumar V, Patil VU, Sharma V (2023) Evaluation of processing quality attributes of potato (*Solanum* spp.) genotypes grown in Mid-Hills of Himachal Pradesh. Potato Res 67:901–929. https://doi.org/10.1007/s11540-023-09646-4

Roe MA, Faulks RM, Belsten JL (1990) Role of reducing sugars and amino acids in fry colour of chips from potatoes grown under different nitrogen regimes. J Sci Food Agric 52:207–214

Scanlon MG, Pritchard MK, Adam LR (1999) Quality evaluation of processing potatoes by near infrared reflectance. J Sci Food Agric 79:763–771

Shimelis H, Shiringani R (2010) Variance components and heritabilities of yield and agronomic traits among cowpea genotypes. Euphytica 173:383–389

Slater AT, Wilson GM, Cogan NOI, Forster JW, Hayes BJ (2014) Improving the analysis of low heritability complex traits for enhanced genetic gain in potato. Theor Appl Genet 127:809–820. https://doi.org/10.1007/s00122-013-2258-7

Slater AT, Wilson R, Holloway PJ (2014) Evaluating the performance of potato varieties for low-heritability traits using best linear unbiased predictors. J Agric Sci 152:3–16

Statista (2022) Potato industry worldwide - statistics & facts. https://www.statista.com/topics/6003/potato-industry-worldwide/#topicOverview. Accessed 25 Jul 2023

Tesfaye A, Wongchaochant S, Taychasinpitak T, Leelapon O (2012) Dry matter content, starch content and starch yield variability and stability of potato varieties in Amhara Region of Ethiopia. Witthayasan Kasetsat Witthayasat 46:671–683

Tessema L, Mohammed W, Abebe T (2020) Evaluation of potato (*Solanum tuberosum* L.) varieties for yield and some agronomic traits. Open Agric 5:63–74. https://doi.org/10.1515/opag-2020-0006

Tessema GL, Mohammed AW, Abebe DT (2022) Genetic variability studies for tuber yield and yield attributes in Ethiopian released potato (Solanum tuberosum L.) varieties. Peer J 10:e12860. https://doi.org/10.7717/peerj.12860

USDA (United States Department of Agriculture) (1997) United States standards for grades of potatoes for processing. U.S. Department of Agriculture, South Building, Washington, DC 20250, pp. 7–8. https://www.ams.usda.gov/sites/default/files/media/Potatoes_for_Processing_Standard%5B1%5D.pdf. Accessed 7 Dec 2023

Visscher PM, Hill WG, Wray NR (2008) Heritability in the genomics era - concepts and misconceptions. Nat Rev Genet 9:255–266

Wassu M (2017) Genetic gain of tuber yield and late blight [*Phytophthora infestans* (Mont.) de Bary] resistance in potato (*Solanum tuberosum* L.) varieties in Ethiopia. East Afr J Sci 11:1–16

Authors and Affiliations

Ntombokulunga W. Mbuma[1,3] · Philippus J. Steyn[2] · Sunette M. Laurie[1] · Maryke T. Labuschagne[3] · Michael W. Bairu[1,4]

✉ Ntombokulunga W. Mbuma
mbuman@arc.agric.za

[1] Roots, Tubers and Bulbous Crops Division, Agricultural Research Council-Vegetable, Industrial and Medicinal Plants, Private Bag X293, Pretoria 0001, South Africa

[2] Farmer Support, Commercialization and Enterprise Development Division, Agricultural Research Council-Vegetable, Industrial and Medicinal Plants, Private Bag X293, Pretoria 0001, South Africa

[3] Department of Plant Sciences, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa

[4] Food Security and Safety Focus Area, Faculty of Natural and Agricultural Sciences, North-West University, Private Bag X2046, Mmabatho 2735, South Africa