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GENOTYPE X ENVIRONMENT INTERACTION, STABILITY AND CO-HERITABILITY OF TUBER INTERNAL QUALITY TRAITS IN POTATO (*SOLANUM TUBEROSUM* L.) CULTIVARS IN ETHIOPIA

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ABSTRACT

Potato (*Solanum tuberosum* L.) is a crop with the potential of ensuring food and nutrition security in Ethiopia because it yields more edible energy, protein and dry matter per unit area and time than cereal crops. In Ethiopia, potato varieties were developed mainly to fit preparation of traditional foods. However, French fries and chips are the emerging products of tubers that demanded breeders to identify cultivars fit to the emerging economics of production until specific varieties are developed for specific end products. This study was conducted with the aim of identifying wide adaptable potato varieties for internal quality of tubers, and to determine stability, coheritability and correlation among traits. A total of 17 improved and two farmers' cultivars namely, Jarso and Bete were evaluated in three locations from 2012 to 2014 using a randomized complete block design with three replications. Specific gravity and starch content of tubers were significantly influenced by the interaction of cultivar x location x seasonwhile dry matter was significantly affected only by cultivar, location and growing season. The 15 improved varieties produced tubers with >1.08 gcm^{-3},>23% and >13%specific gravity, dry matter and starch content, respectively, that were suitable for French fries and chips processing, but the two farmers' cultivars (Jarso and Bete) with tubers <1.080 gcm^{-3} specific gravity and ≤20% dry matter content failed to be processed into French fries and chips. Bubu and Gera were relatively more stable varieties in producing tubers with uniform specific gravity, dry matter and starch content across environments. The other four varieties (Belete, Gudanie, Chirro, and Gorebela) produced tubers with high mean values for all the traits that may be considered for French fries and chips making. Tubers dry matter and starch contents were highly expressed by specific gravity (R^2≥0.96) with strong correlation (r≥0.98) and high coheritability (≥79.85%) of traits with specific gravity. Moreover, high coheritability was observed (86.65%) for the three traits as covariate. This suggests that tuber specific gravity is an appropriate measurement in selection of varieties to determine the internal quality of tubers for processing. The significant effect of genotype x environment interaction on specific gravity and starch content suggests the importance of testing varieties across locations over years to identify high performing and widely adaptable varieties to benefit producers, processors and other consumers.

Key words: Chips, dry matter content, French fries, specific gravity, starch content

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INTRODUCTION

The high yield potential of potato and its plasticity to environmental regimes makes it as one of the best crops for food and nutrition security in Eastern Africa [1]. The potato is a versatile food crop and a source of cheap human diet in many countries. It is the third most important food crop in terms of consumption in the world after rice and wheat [2, 3]. On average, the dry matter content of potato tuber is 20% and the large proportion (60 to 80%) of dry matter is composed of starches, making it a food rich in carbohydrates [4]. It surpasses wheat, rice and maize in terms of dry matter and protein per unit of area. The biological value of potato protein (about 71% that of whole egg) is better than of wheat (53%), maize (54%), peas (48%), beans (46%) and is comparable to cow's milk (75%) [5,6]. Besides supplying carbohydrates and an often diet-deficient amino acid (lysine), potato is a good source of minerals, nutrient salts and several vitamins [7]. Potato is also used for industrial purposes such as starch in textile, paper making, glue, bioreactors for biopharmaceuticals for encapsulation and controlled release of functional ingredients [8] and designer starches [9].

The use of potato is shifting from fresh products into commercial processed foods such as French fries and chips. The tuber specific gravity, dry matter and starch contents are critical in determining the quantity and quality of both products of industries (starch) and processed foods (French fries and chips) [10, 11]. For French fry and potato chips industries, breeding for reduced sugar content, acceptable specific gravity, dry matter and starch contents is a primary goal [12]. Therefore, selection of varieties is not only for high yield, but also for internal quality of tubers. All cultivars are not suitable for the production of processed products. Potato cultivars with tuber dry matter content of 20 to 24% are ideal for making French fries and should have a specific gravity value of more than 1.080. Tubers with less than 1.070 are generally unacceptable for processing [13]. Significant influence of environment, genotype x environment interaction on specific gravity and tuber dry matter content was also reported in Ethiopia [14, 15] and other countries [10, 11, 16].

Potato is a crop with potential to ensure food and nutrition security in Ethiopia. Approximately, 1.3 million farmers grow potato in mid and highlands of Ethiopia and the area planted with potato increased from 30,000 to about 164,146 hectares between 2002 and 2007 [17]. In Ethiopia, more than 27 potato varieties were developed and registered by the government research institutions starting 1987 [18]. The varieties were developed for high yield and resistance to late blight and mainly for traditional meals and dishes but not for other processed products (chips and French fries). However, a substantial amount of potato produced is exported to neighboring countries, particularly from eastern Ethiopia [19] and the use of chips and French fries in cities is increasing [14]. Limited information is available about the suitability of released varieties and farmers' cultivars for chips and French fries making in Ethiopia in general and eastern Ethiopia in particular [14, 15, 20]. However, some of these studies did not include most of the released varieties and cultivars under cultivation and all the studies were conducted only for one cropping season. Moreover, the coheritability of these traits across locations and seasons has not been studied. Therefore, it is necessary to evaluate potato varieties for internal quality of tubers (specific gravity, dry matter and starch

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contents), assess the correlation and coheritability of these traits, and determine the effect of genotype, environment and genotype x environment interaction due to their implication on heritability of traits [21]. Therefore, this research was conducted with the following objectives: i) to evaluate potato cultivars for internal quality of tubers and identify wide adaptable varieties, ii) to determine the effects of genotype, environment, genotype x environment interaction and stability of tuber internal quality traits, and iii) to estimate the coheritability and correlation of tuber internal quality traits.

MATERIALS AND METHODS

Description of the Study Sites

The field experiment was carried out at three locations namely, Haramaya, Hirna and Arberkete which are considered the representative potato growing areas of eastern Ethiopia. The experiment was conducted for two cropping seasons (2012 and 2013) in all the three locations. In addition, at Haramaya, potato cultivars were evaluated during the 2014 cropping season. This made a total of seven environmental combinations, considering one location and one cropping season as one environment.

Haramaya University research farm is located at 2002 m.a.s.l., 9°41"N latitude and 42°03"E longitude. The area has a bimodal rainfall distribution with annual mean of 760 mm. The long rainy season extends from June to October and accounts for about 45% of the total rainfall. The mean maximum temperature is 23.4^{0}C while the mean minimum annual temperature is 8.25^{0}C [22]. The soil of the experimental site is a well-drained deep alluvial with a sub-soil stratified with loam and sandy loam [23]. Hirna sub-station is situated at a distance of about 134 km to the west of Haramaya. The site is located at 9°12" North latitude, 41°4' East longitude, and an altitude of 1870meters above sea level. The area receives mean annual rainfall ranging from 990 to 1010 mm. The average temperature of the area is 24.0°C [22]. The soil of Hirna is vertisol. Arberekete field experiment was conducted on a farmer's field, which is located at a distance of about 171 km to the west of Haramaya. The site is located at 9°14" North latitude, 41°2" East longitude, and an altitude of 2280 meters above sea level.

Experimental Materials

In this research, a total of 17 potato cultivars of which 15 improved varieties and two farmers' cultivars (Jarso and Bete) were used. The two farmers' cultivars are commonly cultivated in eastern Ethiopia in which the farmers identified the merit and characters of the cultivars through a long period of cultivation. The improved varieties were released by five research centers and Haramaya University during 1998 to 2011 for different agro-ecologies of the country. The description of the varieties is given in Table 1.

Experimental Design and Procedures

The experiment was laid out as a randomized complete block design with three replications in each environment. Each potato cultivar was assigned to one plot in each replication and six rows each with 12 plants. The gross plot size was 16.2 m^2 with 75 and 30 cm spacing between rows and plants, respectively. The spacing of 1.5 and 1.0 m was maintained between plots and replications, respectively.

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Planting was at the end of June and first week of July during the main growing season after the rain commenced and when the soil was moist enough to support emergence. The planting depth was maintained at 10 cm. The recommended rate of Phosphorus fertilizer (92 kg P_2O_5 ha^{-1}) was applied at planting in the form of Diammonium Phosphate. Nitrogen fertilizer was applied at the rate of 75 kg N ha^{-1} in the form of Urea in two splits, half rate after full emergence and half rate at the initiation of tubers.Other agronomic managements were applied as per the recommendation made for the crop. The haulm was mowed two weeks before harvesting to thicken tuber periderm.

Data Collection

Tubers were carefully collected after the hills were hand dug. Tuber dry matter content (%) was measured from five fresh tubers in each plot. The randomly selected tubers were weighed at harvest, sliced and dried in oven at 75^{o}C until a constant weight was obtained and dry matter percent were calculated as per the established procedure [24].

$$\text{Dry matter (\%)} = \frac{Weight\ of\ sample\ after\ drying\,(g)}{Intial\ weight\ of\ sample\,(g)} \text{ x 100}$$

Specific gravity of tubers was measured using weight in air and weight in water method. Five kg tubers of all shapes and sizes were randomly taken from each plot and washed with water then weighed first in air and then in water. The specific gravity of tubers was calculated using the following formula [25]:

$$\text{Specific gravity (gcm}^{-3}\text{)} = \frac{Weight\ in\ air}{Weight\ in\ air - Weight\ in\ water}$$

Total starch content (%) was estimated from specific gravity. Starch (%) =17.546 + 199.07 × (specific gravity-1.0988) [26] where specific gravity was determined as indicated above by the weight in air and weight in water method.

Data Analysis

Data were subjected to analysis of variance (ANOVA) for each location and combined over environments following the standard procedure using SAS software version 9.1 [27]. Further genotype x environment interaction (GEI) and stability analyses were conducted for tuber specific gravity and starch content since the mean squares of cultivar x location x season were significant for these traits. Mean values of cultivars were compared using Least Significant Differences at 5% probability.

Analyses of variance were computed for seven environments using Additive Main Effects and Multiplicative Interaction (AMMI) [28] and regression [29] models. Regression coefficient (bi) and deviation from linear regression (Sdi^2) [29], and from AMMI model [28], interaction principal component axes (IPCA) scores of genotype and environment stability parameters were computed. In AMMI biplot, main effects (genotype and environment means) were plotted on the abscissa and the IPCA 1

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scores for the same cultivars and environments on the ordinate [28]. In addition, AMMI stability values (ASV) were calculated [30] for each cultivar.

$$\textbf{ASV=}\sqrt{\left[\frac{\text{IPCAISS}}{\text{IPCA2SS}}\left(IPCA1score\right)\right]^{2}+[\text{IPCA2score})^{2}}$$

Where, ASV=AMI stability value; SS = sum of squares, IPCA1 and IPCA 2 = the first and the second interaction principal component axes, respectively. The cultivars with lower ASV were considered to bemore stable than those with higher ASV values.

Analysis of covariance was also conducted for the three tuber quality related traits over environments following the standard procedure [31]. The coheritability of the covariate traits (specific gravity, dry matter and starch contents) was conducted. In this analysis, the total variation was partitioned into genotypic, phenotypic and environmental convinces as follows:

Environment covariance between character x and y = $\sigma^2 exy$

Genotypic covariance between character x and y ($\sigma^2 g$xy)

$$\sigma^2 g\text{xy} = \frac{Mean\ products\ of\ between\ genotypes - Mean\ products\ of\ within\ \text{var}ieties\ (Error)}{Number\ of\ replications\ x\ Number\ of\ locations}$$

Mean products of between genotypes = Mean products of genotypes minus mean products due to genotype x season, genotype x location and genotype x season x location. Because the mean products of between genotypes include all the interactions (genotype x season, genotype x location and genotype x season x location) since the experiment was conducted across locations and seasons.

Phenotypic covariance between character x and y ($\sigma^2 pxy$) = $\sigma^2 g$xy+ $\sigma^2 exy$

Coheritability (CH^2) = ($\sigma^2 g$xy/$\sigma^2 pxy$) x 100

Linear regression analysis for tuber specific gravity, dry matter and starch contents was conducted for the mean performance of each cultivar at each location and overall mean performance of cultivars over locations. The regression was computed taking tuber specific gravity mean performance of cultivars over years and locations as independent variable and over all mean performance of dry matter and starch contents as dependent (response) variables. The regression equations for specific gravity, dry matter and starch contents were calculated and presented in a graph.

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RESULTS

General Analysis of Variance and Mean Performance of Cultivars

The combined unbalanced analysis of variance over seven environments revealed the presence of significant influence on cultivar, location and season, where the interactions of cultivar x location and location x season had significant influence on tuber dry matter content. However, tuber-specific gravity and starch content were significantly affected by the interaction of the three factors (cultivar x location x season) in addition to the significant effect of the three main factors and one or more of the two factors interactions (Table 2).

The overall mean tuber dry matter content of cultivars ranged from 19.49 (Jarso) to 26.98% (Belete); however, Jarso (19.08%) at Haramaya and Belete (27.18%) at Hirna had very low and hightuber dry matter contents, respectively. The overall mean tuber dry matter content of cultivars was 24.22% (Table 3). The tuber specific gravity and starch content ranged from 1.065 to 1.097 and 10.71 to 16.88%, respectively (Table 6). Belete followed by Bubu, Gera, Gorebela, and Guasa had the highest specific gravity, dry matter and starch contents while the two farmers' cultivars had the lowest (Table 3 and 6). In general, none of the improved varieties had overall mean values of <1.08gcm^{-3}, <23% and <13% specific gravity, dry matter and starch contents, respectively (Table 3 & 6).

Genotype x Environment Analysis of Variance

The mean squares of all sources of variation (genotype, environment, genotype x environment interaction, IPCA I and II) were significant for specific gravity and tuber starch content in AMMI model analysis (Table 4). Aanalysis of variance from Eberhart and Russel's model also exhibited significant mean squares of genotypes, genotype x environment (linear), environment + (genotype x environment) and pooled deviation for starch content and specific gravity except the mean square of pooled deviation was nonsignificant for specific gravity (Table 5).

Treatment sum of squares had highest contribution to total sum squares that accounted for 79.47 and 75.29% for starch content and specific gravity, respectively. The error sum of squares contributed to total sum squares only for 19.8 and 23.68% for starch content and specific gravity, respectively. Genotype sum squares accounted for the highest proportion of 75.46 and 74.96% for treatment sum squares for starch content and specific gravity, respectively, while genotype x environment and environment sum squareshad a lower share. The IPCA 1 sum square contributed the highest share for genotype x environment sum squaresas compared to IPCA 2 and residuals (Table 4).

Stability Analyses

Bulle, Araarsaa,Guasa, Bete, Bubu and Belete ranked the lowest ASV for specific gravity, but only Belete, Bubu and Guasa had highest mean values ($\geq$1.09). Bedasa, Gorebela and Mara Charre were among the cultivars that ranked the highest ASV but had high mean specific gravity. Mara Charre, Chala, Bubu, Bedasa and Gera ranked the lowest ASV for starch content, however, only Bubu and Gera had highest mean starch content (>15%) (Table 6). For starch content, the deviation from regression (S^2di) was

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non-significant from unity for all cultivars, whereas regression coefficient (bi) was significantly different from zero for all except Belete, Chirro, Araarsaa, Gorebela, Mara Charre, Bedasa and Bete. Both S^2di and bi values were nonsignificant for tuber specific gravity in all cultivars.

The AMMI biplot for starch content was constructed and presented in Figure 1. The AMMI bi-plot showed that Gera, Mara Charre, Zemen, Gabbisa, Chirro and Gussa were displayed at top right, while Bedssa, Bete, Ararrsa and Chala were at top left of the quadrant. All the other cultivars were plotted at bottom right except for Jalene which was displayed at bottom left of the biplot quadrant. The five environments were plotted at bottom right whereas Arberkete and Hirna during 2012 cropping season were placed at top right and top left of the quadrants, respectively.

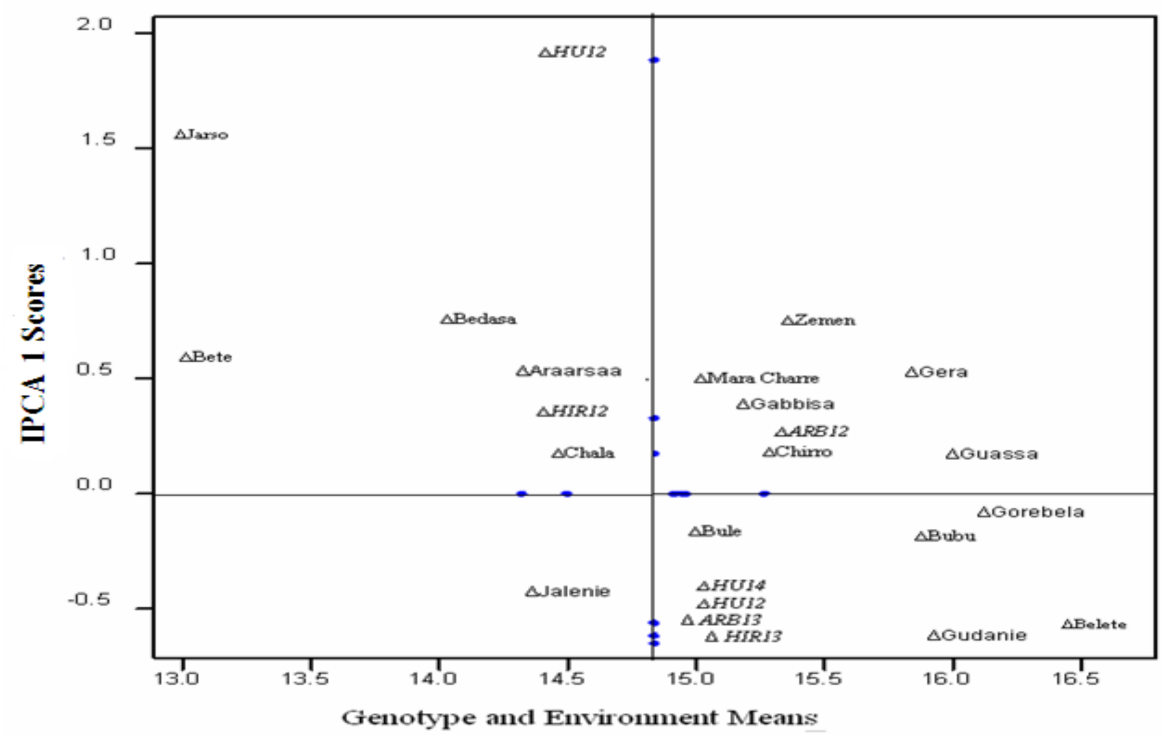

Figure 1: AMMI biplot of 17 potato genotypes evaluated for tuber starch content at seven environments in eastern Ethiopia

Analysis of Covariance and Coheritability

The analysis of covariance (ANCOVA) revealed the significant influence of cultivar, location and season as well as all possible interactions of these covariates. However, dry matter and specific gravity as well as dry matter and starch content as covariate traits were not significantly influenced by the interaction of cultivar x location x season and cultivar x season (Table 7).

The coheritability of tuber internal quality traits ranged from 79.85 (specific gravity and starch content) to 87.02% (dry matter and starch content). The three tuber quality

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traits (dry matter, specific gravity and starch content) as covariate traits had coheritability of 86.65%while dry matter and specific covariate had coheritability of 83.47% (Table 8).

Regression Analysis

The linear regression graph along with the equations is presented in Figure 2. Both tuber dry matter and starch contents were highly expressed by specific gravity. The coefficient of determination for starch content was higher (R^2= 0.97) than dry matter content (R^2= 0.96). The correlation between specific gravity and dry matter (r=0.98) and specific gravity and starch content (r=0.99) were high approaching perfect association.

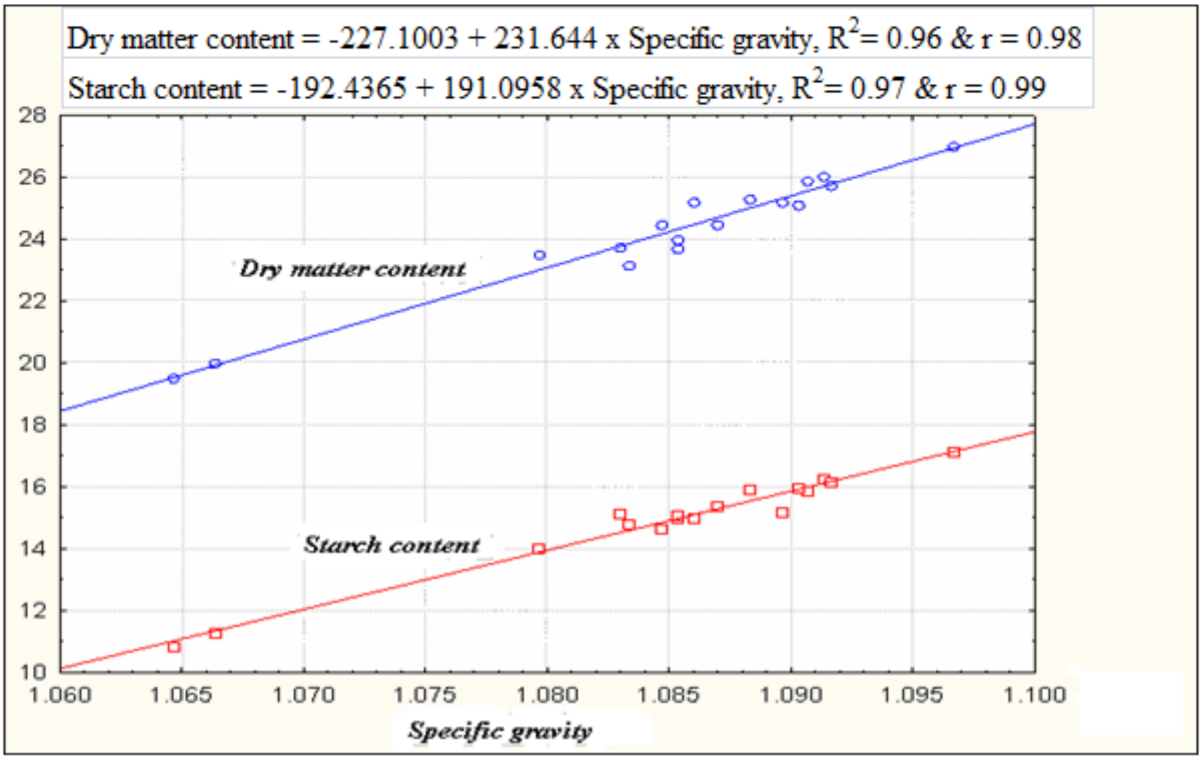

Figure 2: Linear regression of overall mean tuber specific gravity of 17 potato cultivars on overall mean tuber dry matter and starch contents of cultivars with equations of best-fit lines

DISCUSSION

Potato cultivars exhibited significant variations for all tuber internal quality traits. None of the 15 improved varieties had <1.08 gcm^{-3}, <23% and <13% overall mean values of tuber specific gravity, dry matter and starch content, respectively. On the other hand, the two farmers' cultivars (Jarso and Bete) had tubers <1.080 gcm^{-3} mean specific gravity and $\leq$20% dry matter content at different locations and failed to be processed to French fries and chips. Several other authors also reported the variations among varieties in producing tubers with varied quantity of specific gravity, dry matter and starch contents that determine the quality of tubers to be processed as an index of quality French fries and chips [10, 11, 14, 15, 16]. Tubers with dry matter content of 20 to 24% are ideal for making French fries and these tubers are also suitable for preparing crisps. Potato tubers should also have a specific gravity value of more than 1.080 and those with less than 1.070 are generally unacceptable for processing [13]. This showed that all improved potato varieties were suitable for French fries and chips making but the farmers' cultivars (Jarso and Bete) were not.

The significant influence of location and growing season on all tuber internal quality traits suggested the need to test cultivars across locations over seasons to identify varieties that fit for the intended end use. In addition, specific gravity and starch content were significantly influenced by the interaction of cultivar x location x season indicating the unstable expression of these traits in different cultivars across locations and seasons. These quality traits are genetically controlled and also influenced by growing locations and seasons [10, 11, 15, 32]. Specific gravity and tuber dry matter content are influenced by both the environment and genotype [14, 16]. In the presence of significant influence of location and growing season, it is necessary to develop wide adaptable potato varieties. These varieties can produce the same specific gravity or dry matter when grown in differing environments and supply more uniform products that benefit producers, processors and other consumers [33].

The predominant factor to determine the internal quality of tubers was the inherent characteristics of cultivars and locations. These quality traits are genetically controlled and also influenced with growing locations and seasons [10, 11, 32]. However, analysis of GEI from the two models showed the significant influence of genotype x environment interaction on specific gravity and starch content. This indicates that some of the cultivars rank different in different environments, which emphasizes the need to breed specific varieties that perform better in specific environment(s) [21]. However, developing a specific variety for a specific environment is resource consuming that may not be affordable in less developed countries. In such a case, stability is becoming the key issue and hence the importance of developing varieties that outperform consistently other competing genotypes and perform well over a range of environments [34]. The GEI analysis results from both models suggested the importance of testing of many cultivars across locations and seasons, to identify wide adaptable varieties that could produce tubers with uniform specific gravity and starch content in all environments.

All improved varieties had a required tuber quality for quality French fries and chips making. Potato cultivars producing tubers with dry matter content $\geq$20% and specific gravity $\geq$1.080 [13] as well as starch content $\geq$13% [35] are the most preferred for processed products. In this regard, the potato improvement program in Ethiopia was on the right track since all varieties were fit for general purpose, including for French fries and chips processing. However, varieties were varied for stability of tubers internal quality. In this situation, it is necessary to consider the stability parameters along with high performance although the varieties can be responsive to changing environments (dynamic stability) [36]. Bubu, Belete, Gera, Gudanie, Chirro, and Gorebela had higher mean values for all tuber internal quality traits across

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locations. These varieties can be recommended for all purposes including the production of French fries and chips. Moreover, Bubu and Gera were relatively more stable than other varieties for internal quality of tubers with high mean values, suggesting the wide adaptability of the varieties and can be recommended for production in both favorable and unfavorable environments. In choosing superior genotypes, a low or minimal genotype x environment interaction must exist [37].

All locations at different cropping seasons plotted in three of four quadrants of the AMMI biplot indicated that the starch content of tubers did not show static stability. Static stability is when the genotype performance is not changing from one environment to another while the dynamic stability is when genotypic responses are changing as the testing environments change [34]. The regression coefficient (bi) being significant for most varieties also suggested that most of the varieties were responsive for the changing environments [29]. This research result showed that it is important not to evaluate varieties only at a single location over seasons or at different locations only for one season. It suggested the evaluation of varieties for starch content at different locations over seasons.

The highest coheritability of the three covariate traits (specific gravity, dry matter and starch contents) and strong correlations of the three traits suggested that the environment favoring or disfavoring one of the traits also had similar effects on the other two traits. It has been suggested that traits with high genotype x environment interaction have low heritability, which adversely affects the ability to select superior genotypes for all environments [21]. However, these experimental results indicated that the significant effect of genotype x environment interaction on specific gravity and starch content did not adversely affect the coheritability of the three traits. The observed linear relationship of specific gravity with tuber dry matter and starch contents with high coefficient of determination suggested the selection of superior cultivars for tuber specific gravity was also the simultaneous selection of the superior cultivars for other two traits. Tuber dry matter content and tuber specific gravity had high and positive correlation and the two traits reflect the amount of starch present, which are all used as crude indicators of processing quality [38]. Specific gravity is a true indicator of the amount of tuber dry matter content due to positive and significant correlation of the two traits [39].

CONCLUSION

The improved potato varieties under study were released in Ethiopia following their high tuber yields and resistance to late blight disease. However, the understanding of the tuber internal quality traits is just as important as tuber yield since the improvement of varieties for high yield alone cannot guarantee the satisfaction of the end users. The potato varieties under cultivation in different agro-ecologies of Ethiopia showed significant variations for tuber specific gravity, dry matter and starch contents. All improved varieties were fit to be processed to quality French fries and chips. However, the observed significant effect of genotype x environment interaction on specific gravity and starch content indicates the importance of testing varieties across locations over years to identify high performing and wide adaptable ones to benefit producers, processors and other consumers. The research also showed that selection of varieties for high tubers specific gravity is the simultaneous selection for dry matter and starch contents and thereby the determination of internal quality of tubers for processing. Therefore, it can be concluded that the measurement of tubers specific gravity is sufficient at each level of variety development to determine the suitability of genotypes for different purposes or end products.

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Table 1: Name, accession code, year of release, maintainer center of potato cultivars

No.	Genotype	Accession code	Year of release	Breeding center	Recommended altitude (m.a.s.l.)
1	Araarsaa	CIP-90138.12	2006	Sinnana Research Center	2400-3350
2	Bedasa	AL-114	2001	Haramaya University	2400-3350
3	Belete	CIP-393371.58	2009	Holeta Research Center	1600-2800
4	Bete	Farmers' cultivar			
5	Bubu	CIP-384321-3	2011	Haramaya University	1700-2000
6	Bulle	CIP-387224-25	2005	Hwassa Research Center	1700-2700
7	Chala	CIP-387412-2	2005	Haramaya University	1700-2000
8	Chirro	AL-111	1998	Haramaya University	2700-3200
9	Gabbisa	CIP-3870-96-11	2005	Haramaya University	1700-2000
10	Gera	KP-90134.2	2003	Sheno Research Center	2700-3200
11	Gorebela	CIP-382173.12	2002	Sheno Research Center	1700-2400
12	Gudanie	CIP-386423.13	2006	Holeta Research Center	1600-2800
13	Guasa	CIP-384321.9	2002	Adet Research Center	2000-2800
14	Jalenie	CIP-37792-5	2002	Holeta Research Center	1600-2800
15	Jarso	Farmers'cultivar			
16	Mara Charre	CIP-389701-3	2005	Hwassa Research Center	1700-2700
17	Zemen	AL-105	2001	Haramaya University	1700-2000

Source: Plant Variety Release, Protection and Seed Quality Control Directorate, Crop Variety Register Issue No.16, pp.161-164 (Ministry of Agriculture, 2013, June, Addis Abeba, Ethiopia)

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Table 2: Mean squares from unbalanced analysis of variance for tuber internal quality traits of 17 potato cultivars evaluated at three locations during 2012 to 2014 cropping seasons

Source of variation	DF	DM (%)	SG (gcm^{-3})	Starch (%)
Replication	2	0.456	0.00005058	1.085
Cultivar (G)	16	80.765**	0.00132426**	55.031**
Location (L)	2	51.237**	0.00003343	4.260*
Season (S)	2	8.196*	0.00013145*	4.964*
G x L	32	2.788*	0.00005739	2.555*
G x S	32	2.211	0.00008097*	2.669*
L x S	2	35.758**	0.00008907	7.062*
G x L x S	32	2.229	0.00006724*	2.815**
Error	236	1.782	0.00003885	1.291
CV (%)		5.5	0.57	7.65

* and **, significant at P<0.05 and P<0.01, respectively. DF= degree of freedom, DM (%) = dry matter content in percent, SG (gcm^{-3}) = specific gravity gram per cubic centimeter, Starch g/100g = starch content gram per 100 gram fresh tuber weight and CV (%) = coefficient of variation in percent

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Table 3: Mean tuber dry matter content of 17 potato cultivars at three locations during 2012 to 2014 cropping seasons (seven environments)

Cultivar	Haramaya	Hirna	Arberkete	Overall Mean
Bubu	25.79[a-d]	25.35[b]	26.82[ab]	25.99
Belete	26.63[a]	27.18[a]	27.14[a]	26.98
Chala	25.7[a-e]	24.26[bcd]	25.53[cd]	25.16
Gudanie	25.25[a-f]	24.75[bc]	25.81[c]	25.27
Bulle	24.84[d-g]	22.33[ef]	23.86[efg]	23.68
Chirro	25.93[a-d]	24.49[bcd]	25.16[cd]	25.19
Araarsaa	24.4[efg]	21.81[f]	23.26[g]	23.16
Zemen	25.17[c-f]	23.66[cde]	24.58[de]	24.47
Jalenie	24.87[d-g]	23.05[def]	25.41[cd]	24.44
Jarso	19.08[h]	19.27[g]	20.11[h]	19.49
Gabbisa	23.5[g]	23.83[cde]	24.57[def]	23.97
Gorebela	26.56[ab]	25.13[bc]	25.52[cd]	25.74
Mara Charre	25.21[b-f]	22.34[ef]	23.65[efg]	23.73
Bete	19.88[h]	19.12[g]	20.99[h]	20.00
Bedasa	24.23[fg]	22.63[ef]	23.58[fg]	23.48
Gera	26.27[abc]	25.55[b]	25.84[bc]	25.89
Guasa	25.59[a-f]	23.77[cde]	25.96[bc]	25.11
Mean	24.64	23.44	24.576	24.22
LSD (5%)	2.39	2.123	1.4202	
Year				
2012	24.36	22.65[b]	24.76[a]	23.92
2013	24.62	24.23[a]	24.39[b]	24.41
2014	24.94	--------	--------	24.94
LSD (5%)	NS	0.515	0.344	

Means with similar letter(s) are not significantly different from each other

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Table 4: AMMI analysis of variance for tuber specific gravity and starch content of 17 potato cultivars tested at seven environments (three locations during 2012 to 2014)

Sources of variation	DF	Specific gravity (gcm^{-3})				Starch content (%)			
		Sum of squares	Mean squares	Sum of square explained		Sum of squares	Mean squares	Sum of square explained	
				% total	% G x E			% total	% G x E
Treatment	118	0.02827	0.0002396**	75.29		1165.2	9.875**	79.47	
Genotype	16	0.02119	0.0013243**	74.96		879.3	54.954**	75.46	
Environment	6	0.00051	0.0000847**	1.80		31.3	5.224**	2.69	
Rep within E	14	0.00038	0.000027	1.34		10.7	0.766	0.92	
G x E	96	0.00658	0.0000685**	23.28		254.6	2.652**	21.85	
IPCA 1	21	0.00269	0.0001279**		40.88	126.8	6.039**		49.8
IPCA 2	19	0.00215	0.0001131*		32.67	78.5	4.133**		30.83
Residuals	56	0.00175	0.0000312		26.60	49.3	0.88		19.36
Error	224	0.00889	0.0000397	23.68		290.3	1.296	19.8	
Total	356	0.03755	0.0001055			1466.3	4.119		

* and **, significant at $P<0.05$ and $P<0.01$, respectively. DF= degree of freedom, Rep within E= replication within environments, G x E=genotype by environment interaction, IPCA 1 and 2, interaction principal component axis one and two, respectively

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Table 5: Analyses of variance from Eberhart and Russel's Model for specific gravity and starch content of 17 potato cultivars tested at three locations during 2012 to 2014

Source of variation	DF	Specific gravity (gcm^{-3})	Starch content (%)
Genotypes	16	0.0071**	18.32**
Environment + (Geno x Env.)	102	0.0024**	0.93**
Environment (linear)	1	0.0002**	10.45
Genotypes x Env. (linear)	16	0.0007*	1.55**
Pooled Deviation	85	0.0015	0.71**
Bubu	5	0.0003	0.10
Belete	5	0.0000	0.14
Chala	5	0.0000	0.78
Gudanie	5	0.0000	0.12
Bulle	5	0.0000	0.23
Chirro	5	0.0000	3.23**
Araarsaa	5	0.0001	1.05
Zemen	5	0.0000	0.12
Jalenie	5	0.0000	0.05
Jarso	5	0.0004	2.66*
Gabbisa	5	0.0000	0.04
Gorebela	5	0.0000	0.25
Mara Charre	5	0.0002	1.10
Bete	5	0.0001	0.84
Bedasa	5	0.0002	1.17
Gera	5	0.0000	0.04
Guasa	5	0.0000	0.10
Pooled Error	238	0.0031	0.42

DF= degree of freedom, * and **, significant at P<0.05 and P<0.01, respectively

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Table 6: Stability parameters for tuber specific gravity and starch content of 17 potato cultivars from AMMI and Eberhart and Russel's models analyses at seven environments (three locations during 2012 to 2014)

	Specific gravity (gcm^{-3})						Starch content (%) of tuber					
	Pooled	AMMI model stability			ER's Model stability		Pooled	AMMI model stability			ER's Model stability	
Cultivar	Mean	IPCA 1	IPCA 2	ASV	b_i	S^2di	mean	IPCA 1	IPCA 2	ASV	b_i	S^2di
Bubu	1.091 (3)	0.093	-0.0003	0.028 (4)	0.0967	0.0003	15.84 (4)	0.1	-0.22	0.07 (3)	1.31**	-0.33
Belete	1.097 (1)	-0.021	0.0179	0.031 (5)	0.3451	0.0001	16.88 (1)	-0.22	0.28	0.20 (7)	0.44	-0.28
Chala	1.086 (7)	0.008	-0.1071	0.107 (13)	6.3783	0.0001	14.8 (11)	0.18	-1.45	0.06 (2)	4.41**	0.36
Gudanie	1.088 (5)	0.024	-0.0514	0.053 (10)	3.2309	0.0001	15.84 (4)	0.4	-0.67	0.31(8)	3.21**	-0.31
Bulle	1.085 (8)	0.016	-0.0188	0.023 (1)	1.7403	0.0001	14.97 (10)	0.28	-0.21	0.32 (9)	1.34*	-0.2
Chirro	1.090 (4)	0.014	0.0391	0.039 (8)	-1.015	0.0001	15.25 (7)	1.51	0.18	4.34 (16)	1.75	2.8
Araarsaa	1.083 (9)	-0.015	0.0101	0.023 (1)	0.3299	0.0001	14.76 (12)	0.72	0.46	0.90 (14)	1.09	0.63
Zemen	1.087 (6)	0.046	0.0559	0.067 (12)	-2.324	0.0001	15.35 (6)	-0.49	0.71	0.41(12)	-1.55**	-0.3
Jalenie	1.085 (8)	-0.014	-0.0521	0.052 (9)	3.6422	0.0001	14.6 (13)	0.39	-0.48	0.35 (10)	2.94**	-0.37
Jarso	1.065 (12)	-0.086	0.0011	0.066 (11)	2.0037	0.0004	10.71 (16)	-1.51	-0.22	3.96 (15)	-0.321	2.24
Gabbisa	1.085 (8)	0.023	0.0348	0.038 (7)	-0.975	0.0001	15.11 (8)	-0.24	0.39	0.18 (6)	-0.98**	-0.38
Gorebela	1.092 (2)	0.027	0.0035	0.203 (15)	0.5871	0.0001	16.15 (2)	-0.25	-0.09	0.41 (12)	0.04	-0.18
Mara Charre	1.083 (9)	-0.069	0.0092	0.521 (16)	1.2469	0.0002	14.98 (9)	0.06	0.46	0.02 (1)	1.68	0.68
Bete	1.066 (11)	-0.001	-0.0265	0.027 (3)	2.4519	0.0001	11.18 (15)	-0.65	-0.47	0.76 (13)	1.7	0.42
Bedasa	1.080 (10)	-0.059	0.0235	0.149 (14)	0.3875	0.0002	13.97 (14)	0.22	0.72	0.12 (4)	1.05	0.75
Gera	1.091 (3)	-0.001	0.0367	0.037 (6)	-0.823	0.0001	15.82 (5)	-0.24	0.49	0.16 (5)	-0.61**	-0.38
Guasa	1.090 (4)	0.015	0.0245	0.026 (2)	-0.304	0.0001	15.96 (3)	-0.27	0.13	0.39 (11)	-0.14	-0.33
Mean	1.085						14.83					

* and **, significant at P<0.05 and P<0.01, respectively. Numbers in parenthesis represent the pooled mean and ASV rank of cultivars in descending and ascending order, respectively. IPCA 1 and IPCA 1 = interaction principal component axis one and two, respectively, ASV = AMMI stability value, ER's = Eberhart and Russel's mmodel, bi and S^2di, regression coefficient and deviation from regression, respectively

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Table 7: Mean products from analysis of covariance (ANCOVA) for tuber internal quality traits of 17 potato cultivars tested at three locations during 2012 to 2014

Source of variation	DF	DM x SG	DM x STAR	SG x STAR	DM x SG x STAR
Replication	2	0.437	992.12	1.583	1421.102
Genotype (G)	16	110.380**	84420.231**	71.983**	105609.111**
Location (L)	2	60.958**	19205.142**	5.488*	23197.012**
Season (S)	2	11.465*	9177.112**	6.424*	11440.104*
G x L	32	3.465*	2350.431	3.253*	2930.045*
G x S	32	2.861	2775.151**	3.548*	3567.131**
L x S	2	43.309**	19375.102**	9.129*	23678.103**
G x L x S	32	2.876	2295.132	3.610**	2901.005*
Error	236	2.179	1255.011	1.726	1619.002
CV (%)		5.6	9.73	8.15	10.17

* and **, significant at P<0.05 and P<0.01, respectively. DM = tuber dry matter content, DF= degree of freedom, SG = specific gravity and STAR = starch content

Table 8: Genotypic and phenotypic covariances and coheritability of tuber internal quality traits in 17 potato cultivars

Covariate traits	$\sigma^2 g$	$\sigma^2 p$	Coheritability (%)
Dry matter content x specific gravity	11.00	13.18	83.47
Dry matter x starch content	8416.06	9671.07	87.02
Specific gravity x starch content	6.84	8.57	79.85
Dry matter x starch contents x specific gravity	10510.21	12129.22	86.65

$\sigma^2 g$ = genotypic covariance of covariate traits x and y, $\sigma^2 p$= phenotypic covariance of covariate traits x and y, and CH^2 (%) = coheritability of covariate traits x and y in percent

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