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Application of wedge fracture test for texture analysis in boiled sweetpotato (*Ipomoea batatas*)

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Several instrumental texture analysis methods have been developed for use in sweetpotato. However, there are very few reports on the use of the wedge fracture test. The purpose of the study was to develop a texture analysis method using a wedge fracture and evaluate its performance against compression test in assessing sweetpotato varieties with different cooking times. The optimal cooking time (OCT) of five sweetpotato varieties was determined by boiling 2.5 cm^3 cubes until soft. Samples for texture analysis were prepared under four conditions: 85°C for 10 and 15 min; and 95°C for 5 and 10 min. Peak positive force (firmness) and total work done (toughness) were determined using the wedge fracture texture analysis. The correlation between the OCT and texture measurements was evaluated, and samples incubated at 85°C for 15 min had the highest correlation with OCT (R^2 = 0.725). Using this heat treatment, texture measurements from the wedge fracture were compared to those obtained from a compression test. The wedge fracture test gave significant discrimination of sweetpotato varieties ($p \leq 0.05$) while the compression test did not. The wedge fracture test is thus recommended for determining the instrumental firmness of boiled sweetpotato varieties with different cooking times.

Key words: Texture, wedge fracture test, orange-fleshed sweetpotato, optimal cooking time.

INTRODUCTION

Sweetpotato, *Ipomoea batatas* (L) Lam, is ranked as the 5th most important food crop after rice, wheat, maize, and cassava in the developing countries, and ranked seventh in the world food production (FAO, 2016). There is an abundance of white-fleshed sweetpotato (WFSP) varieties across SSA but over the past two decades, the breeding focus has been on producing biofortified orange-fleshed sweetpotato (OFSP) varieties which have enhanced β-carotene (pro-vitamin A) contents. OFSP is a proven, cost-effective method of providing vitamin A to vulnerable populations, especially children and pregnant women (Low et al., 2007, 2017; Sanginga, 2015). Consumer acceptance of new sweetpotato varieties is a major challenge for adoption in both fresh and processing markets and is dependent on the quality and utilization attributes (Tomlins et al., 2004).

Optimal cooking time (OCT) is an important processing factor. Fast cooking varieties are preferred because they utilize less energy, minimize preparation time, and make more nutritious products since there is less time for nutrient loss, conversion to non-bioavailable forms, and undesirable changes in structure and colour. OCT is commonly determined by probing samples with a fork/knife during boiling (Sjölin et al., 2018). This method is subjective but has been successfully applied by other researchers studying potato and sweetpotato because it is easy to perform, without affecting the cooking process in the rest of the batch (Blahovec and Esmir, 2001; Coelho et al., 2007). It is, however, imperative to calibrate the operators to exert the same amount of force while assessing the extent of cooking, and to minimize fracture of the samples as this will change the heating dynamics and cause a bias in the rate of cooking. OCT has also been determined as the time taken to reach a core temperature of 94 to 96°C (Leighton et al., 2010; Sjölin et al., 2018). This temperature, however, is not a widely accepted indicator for cooking and varies with product. Whichever method of choice, it is important to assess the reproducibility and discriminative power when analyzing a large sample set.

The most common preparation methods in sweetpotato are boiling, steaming, roasting, and frying (Oke and Workneh, 2013). In such cooked products, texture is one of the most important sensory attributes determining consumer acceptance (Laurie et al., 2013; Nwosisi et al., 2019; Tomlins et al., 2004). Texture impacts mouthfeel properties (hardness, gumminess/chewiness, moistness, mealiness, smoothness, and stickiness) and is correlated with several physical properties including dry matter content (mainly starch content) and distribution, starch swelling pressure, cell size, cell wall structure, and composition, and the breakdown of the cell wall middle lamella during cooking (He et al., 2014; Kitahara et al., 2017; Ross et al., 2011).

The sensory texture is commonly assessed by quantitative descriptive analysis (QDA) using a panel of trained individuals. However, QDA is inherently low throughput and relatively expensive to implement (Ross et al., 2010). Several instrumental analysis methods have been developed to correlate and complement sensory evaluation because they are less expensive and have a higher throughput. Texture analysis instruments conduct uniaxial tests in which a single or double compression (texture profile analysis; TPA) is performed. During TPA, the instrument simulates mastication by partially compressing the sample twice, to imitate the first two bites taken, while measuring the changes in force over time (Peleg, 2019). Several textural parameters such as hardness, brittleness, chewiness, gumminess, elasticity, adhesiveness, cohesiveness, and springiness are extrapolated from the texture profile. Laurie et al. (2013) reported that instrumental measurements from a TPA curve can reliably predict sensory textural properties. The single compression tests in sweetpotato have been used successfully by Sato et al. (2018) but also been reported to inadequately predict the sensory response (Leighton et al., 2010).

A wide range of special texture measurement devices and probes have been developed. Flat end cylindrical probes of various diameters have been applied for texture analysis of cooked sweetpotato (Ellong et al., 2014; He et al., 2014; Sajeev et al., 2012; Sato et al., 2018). Blade/Shear probes such as the Kramer cell (multiple blades), Warner Bratzler (single blade) and razor blades have mostly been reported for meat products, with a few reports of their use in sweetpotato (Gallego-Castillo and Ayala-Aponte, 2018; Leighton et al., 2010; Sajeev et al., 2012). A wedge fracture/shearing test first developed by Vincent et al. (1991) utilizes an acrylic blade to cut through a cooked sample. This method is relatively easy to perform, and the acrylic blade is affordable. The test was developed to measure peak force and the total work done. The peak force is the maximum force at the onset of an unstable crack, or the force required for the wedge to initially cut and then force the tissue apart and propagate a crack in the cube ahead of the wedge (Ross et al., 2011; Vincent et al., 1991). This relates to the fracturability of the product; the lower the peak force, the more brittle or crunchy the sample is. Total work done refers to the total energy required to penetrate to a pre-determined distance. This is equated to toughness and is represented by the area under the curve. Newer texture analysis protocols include hardness, which is determined as the peak positive force or the maximum force recorded during the test. In some products, peak force and peak positive force coincide at the same point.

There are few reports on the use of the wedge fracture test in the analysis of sweetpotato texture. Therefore, the objectives of this research were to: (i) develop a wedge fracture test suited for determining firmness/hardness in boiled sweetpotato, and (ii) assess the reliability of the

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wedge fracture against compression test.

METHODOLOGY

Development of a wedge fracture test for firmness determination

Sweetpotato roots were harvested at maturity, from an experimental field trial at the National Crops Resources Research Institute (NaCRRI), Namulonge, Uganda. Five varieties were selected and analyzed 3 days after harvest; Ejumula (orange-fleshed), Kyambogo (white-fleshed), NASPOT 8 (pale orange-fleshed), NASPOT 11 (cream-fleshed), and NAROSPOT 1 (pale yellow-fleshed). Three damage-free, representative sized roots were selected, washed under running tap water to remove surface debris and air-dried.

Optimal cooking time

From each root, cubes of 2.5 x 2.5 x 2.5 cm dimensions (2.5 cm^3) were excised from the middle of each root. The cubes were immersed in a pot of water at 95°C on a gas cooker. The timer was started immediately upon closing the lid. At 10 min, and every 2 to 3 min thereafter, the lid was opened, and the root pieces were probed with a thin wooden stick (toothpick) to assess the extent of cooking. A root was considered cooked when the toothpick was pushed all the way through the center, with minimum resistance. The average time was recorded in min, as the optimal cooking time (OCT).

Heating treatments for texture analysis

To determine the cooking conditions that best discriminate between the textural properties of the sweetpotato varieties, roots from each variety (prepared as above) were subjected to four heat treatments; 85°C for 10 min, 85°C for 15 min, 95°C for 5 min and 95°C for 10 min. The samples were left at room temperature and allowed to cool to a core temperature of 28°C, as determined by using a thermometer probe on replicate samples not used for texture analysis. The choice of temperature/time treatments was based on preliminary findings; boiling for up to 20 min resulted in soft samples with poor discrimination of firmness between varieties, thus the temperatures were reduced slightly, to still maintain conditions closer to home cooking.

Texture analysis

The texture of cooked roots was determined on a TA.XT*Express* texture analyzer (Stable Micro Systems, UK) equipped with a 10-kg load cell. The wedge fracture test makes use of a wedge to cut through a sample at an angle, and force tissue apart while propagating a crack in the cube ahead of the wedge (Ross et al., 2010; Vincent et al., 1991). In these experiments, the wedge fracture test was adapted by cutting the sample once, across the fibres (transversely), with a Perspex blade probe (A/LKB) penetrating the sample with an angle of 34°. The test was conducted at a speed of 2 mm/s to a target distance of 10 mm.

Comparison of wedge fracture and compression tests

To determine the applicability of the wedge fracture method developed in 2.1, it was compared to a compression test, commonly used for sweetpotato (Ellong et al., 2014; He et al., 2014; Sajeev et al., 2012; Sato et al., 2018). A different set of sweetpotato varieties were used, to assess how the test performs over a wide range of samples.

Materials

Sweetpotato roots were obtained from farmers in and around Western Kenya and analyzed 4 days after harvest. Five varieties with varying flesh colours were selected; Kabode (orange-fleshed), Irene (dark orange-fleshed), Bungoma (yellow-fleshed), Namnyekere (cream-fleshed), and Mugande (cream-fleshed). The roots were washed under running tap water to remove surface debris, and air-dried.

OCT and texture analysis

From each variety, five roots were selected, prepared and the OCT determined as outlined earlier. For texture analysis, cubes of 2.5cm^3 size were cut from the middle of each root, heated in a water bath at 85°C for 15 min, and cooled to a core temperature of 28°C. Texture measurements were conducted on five roots from each variety, on a texture analyzer (TA.XT, Stable Micro Systems, UK) equipped with a 50-kg load cell. A shearing/wedge fracture test was performed with an acrylic blade probe (A/LKB) cutting into the sample across the fibers (transversely) to a target distance of 10 mm at a speed of 2 mm/s. A compression test was performed with a 5 cm diameter cylinder probe (P/50); the sample was compressed to a target distance of 6 mm at a test speed of 2 mm/s. A shorter compression distance was used for the compression test to minimize the complete disintegration of the sample during analysis.

Data analysis

For all texture analyses, the data collection and calculations were completed using the Exponent Lite Express software v6.1.16.0 (Stable Micro Systems, UK). Firmness/Hardness was measured as peak positive force while toughness was measured as the total work done, represented by the positive area under the curve. The texture data was analyzed on Minitab 19® Statistical software (www.minitab.com) using ANOVA at the 5% significance level, to determine if the texture method was discriminatory. The Tukey HSD test was conducted to determine which varieties were significantly different.

RESULTS AND DISCUSSION

Effect of various heat treatments on texture

The textural properties were directly affected by the cooking temperature and incubation time. The samples cooked at 95°C for 10 min had the lowest instrumental texture (firmness and toughness) values, that is they were the softest, while those incubated at 85°C for 10 min had the highest texture values (Figure 1). Similarly, in a study by Binner et al. (2000), sweetpotato cooked at a lower temperature of 70°C for 30 min had a firm, non-mealy texture while cooking for only 10 min at 100°C had in a soft, mealy/floury texture.

Firmness decreases as cooking progresses, due to the physical and structural changes that occur as a result of

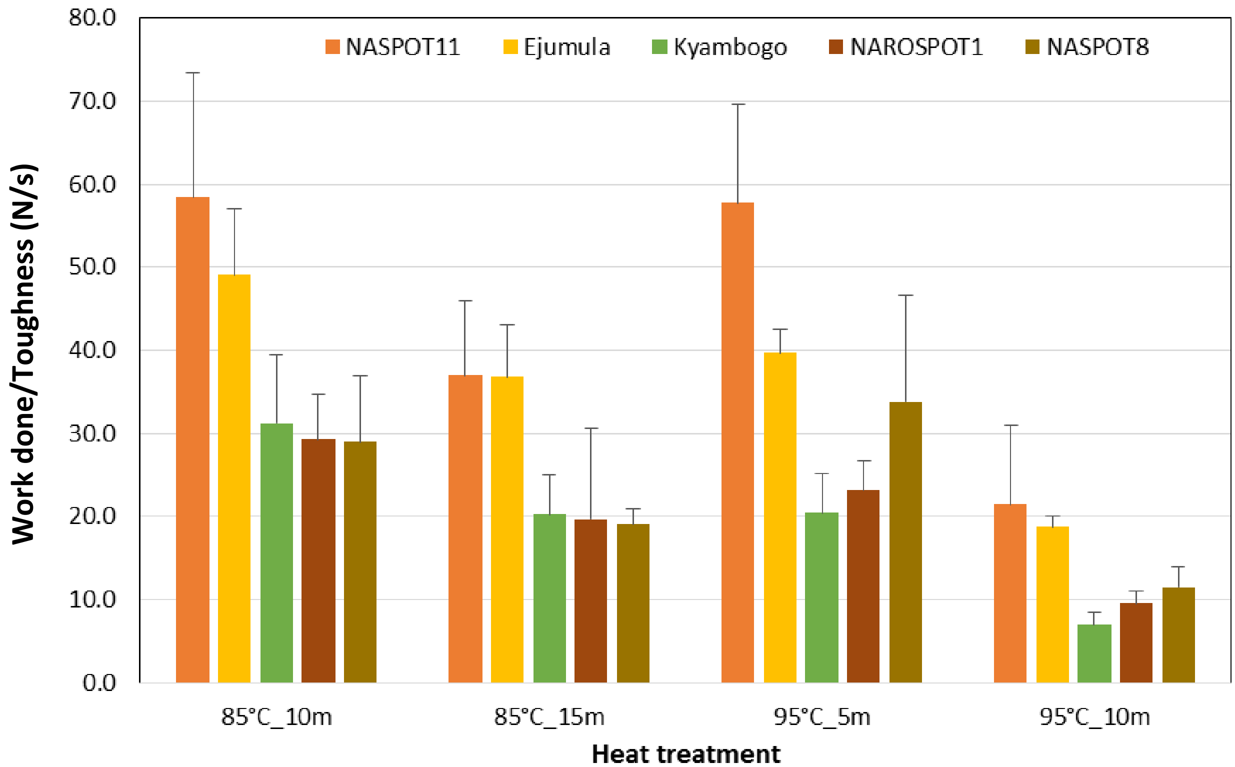

Figure 1. Texture (toughness) of sweetpotato roots prepared by different heat treatments. Graphs represent mean values with standard deviations as error bars.

heat and enzymatic activity. Starch swelling, gelatinization, and hydrolysis associated with changes in cell pressure and cell wall structure are the main contributors to loss of firmness (Gallego-Castillo and Ayala-Aponte, 2018; Sjölin et al., 2018; Valetudie et al., 1999). These biophysical/ biochemical changes are dependent not only on the composition but also on the intensity of cooking.

With regards to individual varieties, the overall ranking (hardest to softest) at 85°C was NASPOT 11 > Ejumula > Kyambogo > NAROSPOT 1 > NASPOT 8, while at 95°C the ranking was NASPOT 11 > Ejumula > NASPOT 8 > NAROSPOT 1 > Kyambogo (Figure 1). At 85°C, NASPOT 8 was the softest, while at 95°C, Kyambogo was the softest. Thus, the extent of softening at the different temperatures appears to be variety-dependent.

At temperatures around 55 to 75°C, cell wall modifying enzymes such as pectin methyl esterases (PMEs) are activated. These modify cell walls by replacing the methyl groups from polyuronic acids with calcium ions, forming stable calcium egg-box structures that strengthen the cell walls (Binner et al., 2000; Liu and Scanlon, 2007; Ross et al., 2010, 2011) and as a result increases firmness. However, cooking at higher temperatures of 80 to 100°C for longer periods results in rapid loss of firmness. In this study, such high temperatures were employed, but with shorter cooking periods to maintain some integrity to the samples, to allow analysis and discrimination amongst genotypes. Such PME related changes also rely on the initial degree of pectin methylation in the cell walls, which might be variety-dependent. The amount of starch, gelatinization properties, and subsequent hydrolysis is also important to texture development. At temperatures around 60 to 90°C, a thermostable β amylase enzyme hydrolyses gelatinized starch into maltose and maltodextrins which leak out of the cell wall resulting in a reduction of cell swelling pressure. This reduces the degree of cell separation during cooking and leads to a brittle, firm, non-mealy texture (Binner et al., 2000; He et al., 2014). Thus, the rate and extent of hydrolysis have an impact on the cooked texture of sweetpotato storage roots.

Relationship between OCT and texture

The OCT ranged from 12 (NAROSPOT 1) to 54 min (Ejumula), showing a great diversity amongst the varieties (Table 1). Ejumula, an OFSP variety, had the longest cooking time, despite the common perception that orange-fleshed sweetpotatoes cook faster and develop a soft and moist texture due to low dry matter contents (Low et al., 2017; Tumwegamire et al., 2005).

Similarly, Truong et al. (1997) reported that the moist/ soggy orange varieties Hernandez, Beauregard, and

Table 1. Optimal cooking times (OCT) for five sweetpotato varieties.

Sweetpotato variety	Flesh colour	OCT (min)
NAROSPOT1	Pale yellow	12*
Kyambogo	White	18
NASPOT8	Pale orange	30
NASPOT11	Cream	39
Ejumula	Orange	54

*OCT reported as the minimum time required for each variety to cook.

Table 2. Correlation between heat treatment and texture measurements.

Treatment	OCT vs. Firmness (R^2)	OCT vs. Toughness (R^2)
85°C_10 min	0.516	0.566
85°C_15 min	0.715	0.725
95°C_5 min	0.549	0.495
95°C_10 min	0.467	0.699

Table 3. Instrumental texture as determined by wedge fracture and compression tests performed in sweetpotato.

Variety	OCT (min)	Wedge fracture test		Compression test	
		Peak positive force/firmness (N)	Work done/toughness (N. s)	Peak positive force/firmness (N)	Work done/toughness (N. s)
Bungoma	18	22.9 (1.5)[b]*	72.6 (4.4)[b]	229.4 (40.3)[a]	301.3 (42.1)[a]
Irene	24	33.6 (3.9)[ab]	108.0 (13.0)[ab]	227.4 (39.1)[a]	218.8 (40.0)[a]
Kabode	33	39.7 (3.9)[a]	129.8 (16.3)[a]	204.4 (19.5)[a]	247.4 (25.5)[a]
Namnyekere	36	34.0 (2.4)[ab]	113.1 (11.0)[ab]	189.9 (9.7)[a]	210.0 (8.0)[a]
Mugande	40	41.1 (2.8)[a]	128.3 (10.9)[a]	220.8 (22.5)[a]	231.1 (28.6)[a]

*Values reported as mean (standard error of mean). Means that do not share a letter in the same column are significantly different ($p<0.05$).

Jewel cooked slowly 18, 19, and 20 min, respectively, while some dry/mealy varieties required between 12.5 and 16 min. Ejumula is one of the few high dry matter (>30%), high β carotene landraces released by the sweetpotato programme in Uganda in 2004 (Mwanga et al., 2007). It is liked by consumers in Kenya and Uganda (Tumwegamire et al., 2005).

The OCT is dependent on several factors such as genotype, physiological age, biophysical/biochemical composition, size of roots, cooking method, and the heat-transfer dynamics during cooking. Large roots tend to cook slower than small-sized roots, as they require more time for heat transfer to the interior. There is thus a need to standardize test samples.

When sweetpotato varieties are assessed at a fixed time before they are fully cooked, the firmness values should discriminate between the fast and slow cooking types. Incubation at 85°C for 15 min resulted in the best correlation between OCT and both peak positive force and work done (Table 2). The higher correlations at 85°C_15 min and 95°C_10 min could have been influenced by the lower range of texture values (Figure 1). In all treatments, except 95°C_5 min, the OCT gave slightly higher correlations with the work done values in comparison with peak positive force values. Either of the parameters could be used as reliable indicators for instrumental texture, however, the work done value could be a more reliable indicator of instrumental texture as compared to peak positive force, a one-point measurement.

Comparison of wedge fracture and compression tests

The sweetpotato varieties used for the comparison study showed a variation of OCT (Table 3), with the yellow-fleshed Bungoma cooking the fastest (18 min) and Mugande, a white-fleshed variety, being the slowest (40 min). The peak positive force and work done values were much higher with the compression test (Table 3). This could be due to the larger 5 cm diameter probe, which

Table 4. Correlation between OCT and texture measurements from wedge fracture and compression tests.

Test	OCT vs. Firmness (R^2)	OCT vs. Toughness (R^2)
Wedge fracture	0.742	0.749
Compression	0.372	0.432

measures the resistance of a wider surface area and the underlying tissues.

The wedge fracture test was discriminatory (ANOVA, $p \leq 0.05$), thus it was able to distinguish the varieties based on the means of the texture measurements. Bungoma, the fastest cooking variety, had significantly lower texture measurements than Kabode and Mugande as expected. The compression test was not discriminatory; the texture measurements from the five varieties were not significantly different from each other (ANOVA, $p \leq 0.05$). The compression test, however, has been reported by other researchers to distinguish varieties; Truong et al. (1997) reported that a 57 mm compression plate resulted in good discrimination of firmness amongst ten sweetpotato varieties, while Laurie et al. (2013) reported that instrumental firmness as determined by a 20 mm diameter probe was more sensitive than sensory firmness in distinguishing twelve sweetpotato varieties. This could be an effect of the varieties used and cooking conditions employed.

The correlation between OCT and texture was higher with the wedge fracture test than with the compression test (Table 4). The OCT, determined by a puncture test, and the wedge fracture measure a more similar property of fracture, whereas the compression test measures deformation properties of the entire sample.

With both tests, there was high intra-variety variation (as shown by SEM values in Table 3). This is typical of root quality traits in most root and tuber crops. Differences in agronomic practices, storage conditions, are all factors that can lead to variability. Many replicates are thus required to account for this. Five replicates were used in this study, other researchers have reported the use of between three up to fifty replicates for each variety (Ali et al., 2012; Laurie et al., 2013; Sato et al., 2018; Truong et al., 1997). Compositional variation has also been observed within the same root, as has been reported in potato tubers (Bandana et al., 2016; Ross et al., 2010). Ross et al. (2010) reported that the stem end of potato tubers of both the Tuberosum and Phureja groups was consistently firmer than the rest of the tuber and could be due to the accumulation of vascular tissue. In sweetpotato, some variations were observed across the root length, although in some varieties it is difficult to distinguish the proximal and distal ends due to the root shape. To avoid such mislabelling, the ends were cut off and all analyses were from the middle part, which represents the bulk of the root. Further studies are required to understand the compositional variation in different varieties.

Conclusion

Wedge fracture is an acceptable method for measuring the firmness of boiled sweetpotato. The wedge fracture correlates well with optimal cooking time when samples are heated at 85°C for 15 min, thus it is ideal for discriminating varieties that vary in cooking times. The work done (positive area under the curve) measurement is a better indicator of firmness, in comparison with peak positive force which is a single point measurement. To be utilized as a substitute for sensory hardness, the performance of the wedge fracture needs to be assessed against sensory data. Also, there is a need to determine its discriminative power on a larger sample size.

CONFLICT OF INTERESTS

The authors have declared any conflict of interests.

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