2018

Physio-Chemical and Functional Properties of Nine Proso Millet Cultivars

Manjot Singh
University of Kentucky, manjot.singh@uky.edu

Akinbode A. Adedeji
University of Kentucky, akinbode.adedeji@uky.edu

Dipak Santra
University of Nebraska - Lincoln

https://doi.org/10.13031/trans.12553

Published in *Transactions of the ASABE*, v. 61, issue 3, p. 1165-1174.

PHYSICO-CHEMICAL AND FUNCTIONAL PROPERTIES OF NINE PROSO MILLET CULTIVARS

M. Singh, A. Adedeji, D. Santra

ABSTRACT. *Evaluation of the postharvest properties of nine proso millet cultivars was carried out to determine their physical and engineering properties, which are very useful for designing appropriate systems for process operations such as sorting, drying, heating, cooling, and milling. Nine cultivars of proso millet comprising waxy and non-waxy types, namely Cope, Earlybird, Huntsman, Minco, Plateau, Sunrise, Rise, Dawn, and Panhandle, were obtained from the Panhandle Research and Extension Center, University of Nebraska, Scottsbluff. Results showed significant ($p < 0.05$) differences in their physical properties, such as sphericity, volume, bulk density, porosity, and angle of repose, which ranged from 0.86 to 0.91, from 3.94 to 5.14 mm^3, from 765.49 to 809.67 kg m^{-3}, from 42.49% to 44.20%, and from 22.98° to 25.74°, respectively. The cultivars were also evaluated for their pasting and gelatinization properties, and high correlation was found between amylose content and onset temperature ($r = -0.94$), peak gelatinization temperature ($r = -0.92$), peak viscosity ($r = 0.84$), final viscosity ($r = 0.91$), and setback viscosity ($r = 0.90$). The understanding of these basic physical and functional properties of proso millet cultivars will form the foundation for processing them into value-added products.*

Keywords. *Chemical properties, Pasting properties, Proso millet.*

Millets are a group of small seeded cereal crops that include many different species of the Poaceae family. Major species in the order of worldwide production are pearl millet (*Pennisetum glaucum*), foxtail millet (*Setaria italic*), proso millet (*Panicum miliaceum*), and finger millet (*Eleusine coracana*) (Ojediran et al., 2010). Millet crops have a unique ability to grow in regions with relatively low rainfall and can tolerate high temperatures and survive drought conditions (Ojediran et al., 2010). Millets are widely grown in Africa and Asia and are one of the major sources of calories in developing countries with harsh natural environments, where often only drought-resistant crops like millet can be grown to combat food insecurity (Saleh et al., 2013). In the U.S., proso millet is the major variety of millet, and it is grown mostly in the states of Colorado, Nebraska, South Dakota, with some limited production in Kansas, Kentucky, Minnesota, and Wyoming (Baltensperger, 2002). The total U.S. production was 305,790 tons in 2014. There has been steady growth in proso millet production in the U.S. in the last decade due to increased demand for export (FAO, 2014). There is also a growing domestic interest in millet in the U.S. because of the increased population of Africans and Asians, who consider millet as an ingredient in food processing, in addition to its potential application in the production of gluten-free foods, extruded snacks, fermented foods, starches, and other factors (Rathore et al., 2016).

Proso millet is a warm-season grass capable of maturing at 60 to 90 days after planting (Baltensperger et al., 1995a). It grows best in full sun, moist to dry conditions, and can perform well in many soil types. Proso millet has higher protein content compared to other varieties of millet and is nutritionally superior to major cereals such as wheat, rice, and corn (Saleh et al., 2013). Significant variations exist among proso millet cultivars in their growth period, seed size, panicle length, plant height, straw strength, amylose-amylopectin starch content, and pasting and gelatinization properties, which necessitate evaluation of the physicochemical properties of the different cultivars. *Panhandle* was developed by the Nebraska Agricultural Experiment Station in 1967, and *Minco* was developed by the Minnesota Agricultural Experiment Station in 1976. Both are similar to the original common white millet but differ slightly in height, yielding ability, and maturity (Robinson, 1976). The University of Nebraska's Panhandle Research and Extension Center released the proso millet cultivar *Dawn* in 1976, which is short in height, with tight panicles, superior white grain, and matures 7 to 10 days earlier than *Panhandle* (Nelson, 1976). A similar variety, *Rise*, developed in 1984 by the same research center, is taller, better yielding, and has tight panicles and smaller white seeds. It is more stable under a wide range of production environments (Nelson, 1984). *Cope* was released by Colorado State University in 1978 and has medium-size white seeds. Due to its maturity, it is best adapted to Colorado conditions and matures five days later than *Panhandle* (Hinze et al., 1978). Three other cultivars (*Huntsman*, *Earlybird*, and *Sunrise*) were released in 1994 and 1995. All three have excellent lodging tolerance, indicating stronger

Submitted for review in July 2017 as manuscript number PRS 12553; approved for publication by the Processing Systems Community of ASABE in February 2018.

The authors are **Manjot Singh,** Graduate Student, and **Akinbode Adedeji,** Assistant Professor, Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky; **Dipak Santra,** Associate Professor, Department of Agronomy and Horticulture, University of Nebraska, Lincoln, Nebraska. **Corresponding author:** Akinbode Adedeji, 128 C.E. Barnhart Building, University of Kentucky, Lexington, KY 40506; phone: 859-218-4355; e-mail: akinbode.adedeji@uky.edu.

Vol. 61(3): 1165-1174 ISSN 2151-0032 https://doi.org/10.13031/trans.12553

stems that prevent bending or breakage during maturity. *Huntsman*, which is a large, white-seeded variety with excellent yield potential, is late in maturity, has closed panicles, good straw strength, and was expected to replace *Cope* in most growing areas (Baltensperger et al., 1995c). *Earlybird* is a large, white-seeded variety with excellent yield potential. It is early in maturity and was expected to replace *Dawn* and *Rise* in most growing areas (Baltensperger et al., 1995b). *Sunrise* is a large, white-seeded variety with excellent yield potential, intermediate maturity, and compact panicles (Baltensperger et al., 1997). *Plateau* is the latest cultivar, released by the Nebraska Agricultural Experiment Station in 2014. It is a cross between *Huntsman* and a Chinese line that is high in waxy starches (Santra et al., 2015). *Plateau* produces grain yields that are competitive with currently grown cultivars and is the first waxy (almost amylose-free) proso millet cultivar (Santra et al., 2015).

Evaluation and knowledge of the physicochemical and engineering properties of these proso millet cultivars is required for designing appropriate equipment for process operations such as sorting, drying, heating, cooling, and milling (Baryeh, 2002). Material quality indicators such as color, hardness, gelatinization, and pasting properties have significant importance in the food industry (Baryeh, 2002). This study also investigated the effects of the amylose-amylopectin starch contents of the cultivars on their pasting and gelatinization properties. This study will help provide new classifications of proso millet cultivars based on their physical, functional, thermal, and pasting properties.

Materials and Methods

Raw Materials

Nine proso millet cultivars, namely *Cope*, *Earlybird*, *Huntsman*, *Dawn*, *Rise*, *Sunrise*, *Plateau*, and *Panhandle*, were obtained from the University of Nebraska's Panhandle Research and Extension Center in Scottsbluff, Nebraska. The cultivars were produced in 2014 at the Dryland Research Farm of the University of Nebraska's High Plains Agricultural Laboratory (HPAL). The harvest moisture was found to be in the range of 7.7% to 10.9%. Seeds from four plots were bulked, and samples were randomly collected and stored at appropriate conditions in a grain silo until this study.

The cultivars were cleaned and sifted to remove foreign materials such as stones, straw, and dirt using a Ro-Tap sieve shaker (RX-29, W.S. Tyler, Mentor, Ohio). The cleaned grains were dehulled using a modified disc mill (Glenn Mills Inc., Clifton, N.J.). In the mill, the stationary disc was replaced with rubber disc to minimize breakage and ensure proper removal of hulls.

Starch Isolation

Starch was isolated using the alkaline steeping method (Singh and Adedeji, 2017; Sira and Amaiz, 2004; Wang and Wang, 2001). Proso flour (100 g) was steeped in 200 mL of 0.1% NaOH for 18 h. The slurry was blended using a Waring blender (model 5011, New Hartford, Conn.) at high speed for 2 min, passed through a 100-mesh sifter, and centrifuged at 1,300×*g* for 10 min. The top layer was carefully removed, and the bottom layer was re-slurried and washed three times with 0.1% NaOH, carefully removing the top layer every time. The starch layer was washed with deionized water and centrifuged. The combined starch was then re-slurried and neutralized with 0.1 N HCl to pH 6.5 and then washed with deionized water four times, centrifuged, and dried in an oven at 45°C for 48 h (Singh and Adedeji, 2017).

Proximate Analysis

Samples were ground using a Quadrumat Junior Mill (C.W. Brabender Instruments Inc., South Hackensack, N.J.), and AOAC Standard Methods were used to determine the moisture (Method 925.09), protein (Method 920.87), crude fiber (method 978.10), fat (Method 920.39), ash (Method 923.03), and carbohydrates (Method 985.29) (AOAC, 2010). Amylose content was determined using AACC Method 61-03.01 (AACC, 2010).

Grain Physical Properties

Millet grains were randomly selected, and 100 grains of each cultivar were scanned using an x-ray micro-computed tomography (CT) scanner (SkyScan 1173, Bruker microCT, Kontich, Belgium) to obtain attenuated images of the grain samples. The x-ray energy is absorbed as a function of the material density. Because the grain edges are uniform, the attenuated energy captured by the photo-detector shows as a uniform grayscale along the edges that allows for distinct delineation of the grain edges for ease of dimensioning. The obtained images were reconstructed using NRecon software (Bruker microCT). CTAn software (Bruker microCT) was used to measure the grains.

The equivalent diameter (D_e), considering a spherical shape for proso millet grains, was determined using the expression described by Hamdani et al. (2014) and Mohsenin (1986):

$$D_e = \left(L^*B^*T\right)^{\frac{1}{3}} \tag{1}$$

where D_e is the equivalent diameter, L is the largest dimension, B is the second largest dimension, and T is the smallest dimension.

The sphericity (Φ) and volume (V) were determined using the following expressions (ElMasry et al., 2009; Mohsenin, 1986):

$$\Phi = \frac{\left(L^*B^*T\right)^{\frac{1}{3}}}{L} \tag{2}$$

$$V = \frac{\pi}{6}\left(L^*B^*T\right) \tag{3}$$

Surface area (S) was calculated using the expression described by Hamdani et al. (2014) and Singh et al. (2010):

$$S = \pi^*\left(D_e\right)^2 \tag{4}$$

Bulk Density and True Density

The bulk density (ρb) was determined by measuring the weight of grains packed in a container of known volume:

$$\rho_b = \frac{\text{measured weight (kg)}}{\text{volume of container (m}^3\text{)}} \quad (5)$$

The solid density (ρ_t) was determined using a multivolume gas pycnometer (model 1340, Micromeritics Instrument Corp., Norcross, Ga.) according to the method of Gely and Pagano (2017).

Grain Porosity

Grain porosity (ε) is defined as the ratio of intergranular void space volume and the volume of the bulk grain. Porosity was determined using the expression (eq. 6) described by Ogunjimi et al. (2002):

$$\varepsilon = 1 - \frac{\rho_b}{\rho_t} \quad (6)$$

Thousand-Kernel Weight

The thousand-kernel weight (TKW) was determined by randomly selecting 1,000 grains from each cultivar and weighing them in ten replicates (Baryeh, 2002). Means and standard deviations were obtained.

Angle of Repose

The angle of repose (Θ) was determined by placing a hollow cylinder, filled with grain, on a steel plate (Rehal et al., 2017). The cylinder was raised gradually until the grain formed a cone, the height (*H*) and diameter (*D*) of the cone were measured, and Θ was calculated using the following expression:

$$\Theta = \tan^{-1}\left(\frac{2H}{D}\right) \quad (7)$$

Hardness

Hardness was measured in 20 replicates using a texture analyzer (TA-XT plus, Stable Micro Systems, Godalming, U.K.). Force was measured in compression mode using the following settings: return to start at 90% strain, pre-test speed of 0.5 mm s^{-1}, test speed of 0.5 mm s^{-1}, and post-test speed of 10.0 mm s^{-1}. Hardness was determined as the maximum force (in kg) during the force displacement through the depth of the seed.

Color Characteristics

The color of the millet cultivars was determined using a digital colorimeter (CR400, Konica Minolta, Tokyo, Japan). The color was determined on the *L*, *a*, *b* scale, where *L* is the degree of lightness or darkness (black to white), *a* is the degree of redness (+*a*) to greenness (-*a*), and *b* is the degree of yellowness (+*b*) to blueness (-*b*).

Gelatinization

Gelatinization properties were determined using differential scanning calorimetry (DSC-Q20, TA Instruments, New Castle, Del.). Flour samples (10 mg, dry basis) were weighed into high-volume stainless steel pans, followed by 20 μL of distilled water to achieve a solid-to-water ratio of 1:2. The pans were hermetically sealed and equilibrated at 4°C for 24 h. The samples were kept at room temperature for 1 h prior to scanning from 10°C to 150°C at 10°C min^{-1} (Singh and Adedeji, 2017).

Pasting Properties

Pasting characteristics were determined using a Discovery hybrid rheometer (DHR-2, TA Instruments, New Castle, Del.) with a starch pasting cell. A mixture of 3.5 g of starch (14% moisture) in 25 mL of distilled water was stirred at 160 rpm. The samples were held at 50°C for 1 min, heated to 95°C at 4°C min^{-1}, and held at 95°C for 5 min. Subsequently, the samples were cooled to 50°C at 4°C min^{-1} and held at 50°C for 5 min. A plot of viscosity (Pa·s) versus time (s) was used to determine the pasting temperature, peak viscosity, final viscosity, and holding strength. Breakdown was calculated as the difference between peak viscosity and holding strength, and setback was calculated as the difference between final viscosity and holding strength (Singh and Adedeji, 2017).

Solubility and Swelling Power

Solubility and swelling power were determined using the method of Leach et al. (1959), as modified by Singh and Adedeji (2017) and Subramanian et al. (1994). Starch (0.1 g) was heated with 10 mL of water at 70°C, 80°C, and 90°C for 30 min. Lump formation was prevented by stirring. The dispersion was centrifuged at 3,000 rpm for 15 min. The supernatant was carefully removed, and the starch sediment was weighed. The supernatant was taken in preweighed petri dishes, evaporated for 2 h at 130°C, and then weighed. The residue obtained after drying the supernatant represented the amount of starch solubilized in water. The result was expressed as:

$$\text{Solubility (\%)} = \left(W_{SS} \times 100\right) / W_S \quad (8)$$

where W_{SS} is the weight of soluble starch (g), and W_S is the weight of the sample (g):

$$\text{Swelling power (\%)} = \frac{\left(W_{SP} \times 100\right)}{\left(W_S \times [100 - \%\text{Solubility}]\right)} \quad (9)$$

where W_{SP} is the weight of sediment paste (g), and W_S is the weight of the sample (g):

Water Binding Capacity

Water binding capacity was determined using the method described by Singh and Adedeji (2017). A suspension of 2.5 g starch (dry basis) in 25 mL of distilled water was agitated for 30 min and centrifuged at 3,000 rpm for 10 min. Excess water was drained for 10 min, and the residual starch was weighed.

$$\text{WBC (\%)} = \left(W_{rs} \times 100\right) / W_s \quad (10)$$

where W_{rs} is the weight of residual starch (g) and W_S is the weight of the sample (g).

STATISTICAL ANALYSIS

The data were analyzed statistically using SAS software (ver. 9.4). When there was a significant effect of the model on the observed variations, the means were separated using Duncan's multiple range test ($p \leq 0.05$). All data are presented as means with standard deviations. Correlation was determined using Pearson's correlation test.

RESULTS

PHYSICAL PROPERTIES

The mean values of the proximate content determined on dry weight basis and the physical properties of the nine proso millet cultivars are presented in tables 1 and 2, respectively. The pre-test moisture content of all cultivars varied from 9.40% to 10.71%. Among the cultivars, the protein content (dry basis) varied from 12.43% (*Rise*) to 15.14% (*Dawn*), whereas fiber and ash were less than 1% in all cultivars. *Cope* showed the lowest fat content of 2.01%, whereas all other cultivars did not have significant ($p < 0.05$) differences in their fat contents (dry basis) and were in the range of 3.26% to 3.85%. Carbohydrate content (dry basis) varied from 80.50% (*Dawn*) to 83.20% (*Rise*). The cultivars had significantly ($p < 0.05$) different amylose contents. *Plateau*, being a waxy millet, had 3.10% amylose, whereas *Minco* had the highest amylose content of 34.60% and *Cope* (18.15%) had the lowest amylose content among all the other cultivars.

Table 2 presents the physical dimensions of the proso millet cultivars, including hardness, TKW, angle of repose, density, and porosity. The variation in length among the cultivars was 2.27 mm (*Huntsman*) to 2.37 mm (*Minco*), whereas the variations in width and thickness were 2.08 mm (*Cope*) to 2.29 mm (*Panhandle*) and 1.59 mm (*Cope*) to 1.84 mm (*Earlybird*), respectively. These dimensions are important for designing grain handling equipment such as sieves, sorters, hullers, and mills. The size and shape of the perforations in such equipment are determined by the dimensions of the seeds (Mohsenin, 1986). Different cultivars of pearl millet

Table 1. Proximate content of proso millet cultivars.[a]

Cultivar	Moisture (%)	Crude Protein (%)	Crude Fat (%)	Crude Fiber (%)	Ash (%)	Carbohydrate (%)	Amylose (%)
Cope	10.29 ±0.02 b	14.38 ±0.06 c	2.01 ±0.08 b	0.57 ±0.06 a	0.68 ±0.02 d	82.86 ±0.12 a	18.15 ±1.06 f
Dawn	9.40 ±0.08 d	15.14 ±0.01 a	3.51 ±0.03 a	0.59 ±0.30 a	0.77 ±0.01 bc	80.50 ±0.06 c	25.10 ±0.28 c
Earlybird	10.18 ±0.06 b	13.78 ±0.05 d	3.60 ±0.13 a	0.94 ±0.35 a	0.83 ±0.08 bc	81.70 ±0.10 b	30.20 ±0.57 b
Huntsman	10.18 ±0.15 b	13.48 ±0.08 e	3.67 ±0.11 a	0.90 ±0.04 a	0.84 ±0.02 bc	81.92 ±0.20 ab	21.40 ±0.57 e
Minco	9.64 ±0.11 cd	13.39 ±0.01 e	3.45 ±0.23 a	0.71 ±0.06 a	0.82 ±0.00 bc	82.24 ±0.25 a	34.60 ±0.28 a
Panhandle	10.35 ±0.03 b	14.34 ±0.03 c	3.85 ±0.04 a	0.84 ±0.28 a	0.90 ±0.04 ab	80.88 ±0.02 bc	26.40 ±0.57 c
Plateau	9.71 ±0.13 c	14.79 ±0.02 b	3.63 ±0.13 a	0.80 ±0.08 a	0.74 ±0.00 cd	80.66 ±0.11 bc	3.10 ±0.28 g
Rise	10.71 ±0.01 a	12.43 ±0.01 f	3.26 ±0.76 a	0.93 ±0.11 a	0.99 ±0.02 a	83.20 ±0.79 a	25.75 ±0.07 cd
Sunrise	9.45 ±0.09 cd	14.20 ±0.01 c	3.59 ±0.07 a	0.81 ±0.01 a	0.98 ±0.01 a	81.12 ±0.05 b	24.40 ±1.41 d

[a] Values are means ± standard deviations of two replicates. Crude protein, crude fat, crude fat, ash, and carbohydrate are calculated as dry basis. Carbohydrate = 100% – (% protein + % fat + % ash). Means in the same column followed by different letters are significantly different ($p < 0.05$).

Table 2. Physical properties of proso millet cultivars.[a]

Property[b]	No. of Replicates	Cultivar								
		Cope	*Dawn*	*Earlybird*	*Huntsman*	*Minco*	*Panhandle*	*Plateau*	*Rise*	*Sunrise*
L (mm)	100	2.29 ±0.14 cd	2.36 ±0.08 ab	2.34 ±0.06 b	2.27 ±0.07 d	2.37 ±0.09 a	2.36 ±0.08 ab	2.27 ±0.13 d	2.30 ±0.06 c	2.35 ±0.07 b
B (mm)	100	2.08 ±0.08 d	2.28 ±0.08 a	2.28 ±0.07 a	2.19 ±0.10 c	2.27 ±0.09 a	2.29 ±0.08 a	2.18 ±0.07 c	2.24 ±0.07 b	2.28 ±0.07 a
T (mm)	100	1.59 ±0.086 f	1.76 ±0.09 b	1.84 ±0.11 a	1.73 ±0.07 cd	1.76 ±0.08 b	1.76 ±0.10 b	1.66 ±0.07 e	1.75 ±0.08 bc	1.72 ±0.08 d
Φ	100	0.86 ±0.04 f	0.90 ±0.02 cd	0.91 ±0.02 a	0.90 ±0.02 bc	0.89 ±0.02 de	0.90 ±0.02 bc	0.89 ±0.03 e	0.91 ±0.02 b	0.89 ±0.02 de
V (mm^3)	100	3.97 ±0.37 g	4.94 ±0.47 bc	5.14 ±0.42 a	4.51 ±0.40 e	4.97 ±0.42 b	4.99 ±0.50 b	4.30 ±0.37 f	4.73 ±0.39 d	4.85 ±0.42 cd
D_e (mm)	100	1.96 ±0.06 g	2.11 ±0.07 bc	2.14 ±0.06 a	2.05 ±0.06 e	2.12 ±0.06 bc	2.12 ±0.07 b	2.02 ±0.06 f	2.08 ±0.06 d	2.10 ±0.06 cd
S (mm^2)	100	12.12 ±0.76 g	14.01 ±0.90 bc	14.39 ±0.79 a	13.19 ±0.79 e	14.08 ±0.79 b	14.11 ±0.94 b	12.79 ±0.74 f	13.62 ±0.75 d	13.84 ±0.81 cd
Bulk density (kg m^{-3})	5	782.56 ±5.02 d	774.30 ±2.86 e	790.38 ±9.45 cd	798.65 ±6.20 b	809.67 ±6.82 a	788.98 ±3.62 cd	765.49 ±5.47 f	795.53 ±5.10 bc	788.65 ±3.52 cd
Solid density (kg m^{-3})	5	1397.72 ±1.22 e	1397.28 ±1.95 e	1411.88 ±0.97 bc	1413.20 ±1.15 b	1417.36 ±1.53 a	1409.94 ±1.53 c	1371.86 ±0.94 f	1410.46 ±1.853 c	1402.68 ±1.931 d
Porosity (%)	5	44.01 ±0.34 abc	44.59 ±0.19 a	44.02 ±0.67 abc	43.49 ±0.46 c	42.87 ±0.53 d	44.04 ±0.29 abc	44.20 ±0.39 ab	43.60 ±0.41 c	43.78 ±0.22 bc
Angle of repose (°)	5	22.99 ±0.73 cd	26.68 ±0.91 a	22.68 ±0.72 cd	21.95 ±0.90 d	23.10 ±0.74 cd	23.70 ±0.98 bc	25.74 ±0.83 a	22.96 ±0.63 cd	24.53 ±0.79 b
TKW (g)	10	4.97 ±0.09 e	5.79 ±0.07 c	6.19 ±0.04 a	6.01 ±0.05 b	5.78 ±0.04 c	5.58 ±0.06 d	4.69 ±0.06 f	6.06 ±0.08 b	6.19 ±0.05 a
Hardness (kg)	20	3.63 ±0.52 b	3.24 ±0.51 cd	3.40 ±0.47 bcd	3.23 ±0.51 cd	3.46 ±0.45 bc	3.33 ±0.45 bcd	4.05 ±0.52 a	3.13 ±0.44 d	3.38 ±0.51 bcd

[a] Values are means ± standard deviations. Means in the same row followed by different letters are significantly different ($p < 0.05$).

[b] L = largest dimension, B = second largest dimension, T = smallest dimension, Φ = sphericity, V = volume, D_e = geometric mean, S = surface area, and TKW = thousand-kernel weight.

had lengths in the range of 3.16 to 3.87 mm, widths of 2.30 to 2.93 mm, and thicknesses of 1.54 to 2.05 mm at 10% moisture content (Ojediran et al., 2010).

The D_e and Φ for the cultivars differed significantly ($p < 0.05$). The mean D_e and Φ varied from 1.96 mm (*Cope*) to 2.14 mm (*Earlybird*) and from 0.86 (*Cope*) to 0.91 (*Earlybird*), respectively. Determination of D_e is important in estimating the projected area, terminal velocity, drag coefficient, and conveying pattern for pneumatic systems. The high sphericity values of the cultivars indicate that proso millet grains have a high rolling tendency, which is important in designing hoppers and other processing equipment (Ghadge and Prasad, 2012). Jain and Bal (1997) reported that pearl millet is more conico-spherical, whereas proso millet is rounder. Ojediran et al. (2010) also reported that pearl millet has lower sphericity (70% to 72%) compared to proso millet (86% to 91%) and lower values for angle of repose, porosity, and solid density.

Among the cultivars, the volume and surface area varied significantly ($p < 0.05$) from 3.97 mm^3 (*Cope*) to 5.14 mm^3 (*Earlybird*) and from 12.12 mm^2 (*Cope*) to 14.39 mm^2 (*Earlybird*), respectively. The surface area and volume are important in calculating the duration and energy requirements for processes such as drying (Alonge and Adigun, 1999).

TKW was found to be in the range of 4.69 (*Plateau*) to 6.19 g (*Earlybird* and *Sunrise*) and was significantly ($p < 0.05$) different among cultivars. TKW is important in determining seeding rates during planting (Miller and McLelland, 2001). The bulk density and solid density varied significantly ($p < 0.05$) from 765.49 kg m^{-3} (*Plateau*) to 809.67 kg m^{-3} (*Minco*) and from 1371.86 kg m^{-3} (*Plateau*) to 1417.36 kg m^{-3} (*Minco*), respectively. The porosity was found to range from 42.87% (*Minco*) to 44.59% (*Dawn*). The TKW, bulk and solid densities, and porosity help in determining transport conditions and the design of hoppers, cleaning and storage equipment. A solid density higher than that of water indicates that wet cleaning can be used because the grain will not float. Bulk density and porosity are important in designing storage bins because these properties help determine the space required for a specified amount of grain and the void area present between grains. Swami and Swami (2010) determined the physical properties of finger millet and reported the true density to be around 1120 kg m^{-3}, the bulk density to be 709 kg m^{-3}, and the sphericity to be 96%. Pearl millet is reported to have higher porosity than proso millet, indicating that pearl millet requires a larger space per unit mass than proso millet to store an equal volume of grain (Jain and Bal, 1997).

The angle of repose varied among cultivars from 21.95° (*Huntsman*) to 26.68° (*Dawn*). This important property is synonymous with the friction between grains. High cohesive forces between grains lead to a higher angle of repose. The angle of repose also provides the maximum slope at which grains are stable, which is important in designing hoppers and silos for proper flow of grain (Baryeh, 2002). Grain hardness determines the milling yield and energy requirements for processing. The hardness of the proso millet cultivars varied from 3.13 kg (*Rise*) to 4.05 kg (*Plateau*). Hardness or cracking force and grain strength help determine the seed resistance to cracking during harvesting and hulling (Mir et al., 2013). Balasubramanian and Viswanathan (2010) studied the effects of moisture on the physical properties of minor millets available in India and reported (at 10% moisture content) proso millet's bulk density to be 899.65 kg m^{-3}, true density to be 1838.5 kg m^{-3}, and porosity to be 52.88%, which are higher than the values found in this study. These differences can be attributed to differences in variety and cultivar, geographical location, and growing conditions. However, the angle of repose obtained for the different cultivars of proso millet in this study are similar to those obtained by Balasubramanian and Viswanathan (2010).

Table 3. Color characteristics of proso millet cultivars.[a]

Cultivar	*L*	*a*	*b*
Cope	76.43 ±1.19 a	-4.47 ±0.59 d	38.12 ±1.31 d
Dawn	72.07 ±1.81 e	-2.57 ±0.81 a	41.27 ±1.99 b
Earlybird	73.31 ±1.51 d	-3.32 ±0.55 b	39.49 ±1.33 c
Huntsman	74.51 ±0.94 c	-3.52 ±0.48 bc	39.38 ±1.40 c
Minco	74.31 ±0.94 c	-3.72 ±0.50 c	41.72 ±1.74 b
Panhandle	75.63 ±0.91 b	-3.50 ±0.39 bc	35.29 ±1.37 e
Plateau	77.13 ±1.17 a	-4.56 ±0.49 d	38.73 ±1.31 cd
Rise	71.80 ±3.62 e	-3.41 ±0.41 b	41.90 ±2.01 b
Sunrise	72.59 ±1.32 de	-2.67 ±0.43 a	43.46 ±1.42 a

[a] Values are means ±standard deviations of 30 replicates. Means in the same column followed by different letters are significantly different ($p < 0.05$).

The colors of the proso millet cultivars, as determined on the *L*, *a*, *b* scale, are presented in table 3. Color is an important factor in seed processing. For example, it can be used to determine the sorting of grain. *Rise* (L = 71.80) was the darkest, whereas *Plateau* (L = 77.13) was the lightest. The *a* value was highest for *Dawn* (-2.57) and lowest for *Plateau* (-4.56). However, the value of *b* was highest for *Sunrise* (43.46) and lowest for *Panhandle* (35.29). The color differences can be attributed to differences in pigments, composition, and genetics of the cultivars (Kaur et al., 2013).

Pasting Properties

The pasting properties of the proso millet cultivars are presented in table 4, and the pasting profiles are shown in figure 1. The cultivars showed significant ($p < 0.05$) differences in their pasting profiles. Based on starch content, the proso millet cultivars can be classified into three categories: low amylose or waxy millet (*Plateau*), medium amylose (*Cope*), and high amylose (*Dawn*, *Earlybird*, *Huntsman*, *Minco*, *Panhandle*, *Rise*, and *Sunrise*). The waxy millet (*Plateau*) showed the lowest peak (0.92 Pa·s) and final (0.71 Pa·s) viscosities, and the medium amylose cultivar (*Cope*) had peak (1.05 Pa·s) and final (1.49 Pa·s) viscosities that were significantly ($p < 0.05$) lower than those of the high amylose cultivars. The low peak viscosities observed in the waxy cultivar can be explained by the fact that starch granule swelling is a property of amylopectin, causing waxy starches to swell rapidly, as indicated by the early onset of pasting temperature. The waxy cultivar (*Plateau*) develops viscosity but cannot maintain the stability of the paste viscosity because heating disrupts the gel structure at reduced amylose content (Tester et al., 2004). Pasting temperature varied from 76.76°C (*Plateau*) to 88.87°C (*Rise*). The high amylose cultivars showed higher pasting temperatures compared to the

Table 4. Pasting properties of cultivars.[a]

Cultivar	Pasting Temperature (°C)	Peak Viscosity (Pa·s)	Holding Strength (Pa·s)	Final Viscosity (Pa·s)	Breakdown (Pa·s)	Setback (Pa·s)
Cope	77.52 ±0.10 f	1.05 ±0.02 e	0.52 ±0.01 d	1.49 ±0.03 d	0.53 ±0.02 d	0.97 ±0.03 e
Dawn	82.05 ±0.81 c	1.62 ±0.01 c	0.74 ±0.01 c	2.84 ±0.04 b	0.88 ±0.01 b	2.10 ±0.04 b
Earlybird	79.06 ±0.39 e	1.91 ±0.03 a	0.83 ±0.01 b	3.15 ±0.01 a	1.08 ±0.04 a	2.32 ±0.01 a
Huntsman	77.31 ±0.77 f	1.80 ±0.01 b	0.77 ±0.01 c	2.24 ±0.01 c	1.03 ±0.03 a	1.47 ±0.02 d
Minco	80.56 ±0.75 d	1.89 ±0.04 ab	0.84 ±0.03 b	2.88 ±0.04 b	1.05 ±0.07 a	2.04 ±0.01 b
Panhandle	80.49 ±0.51 d	1.53 ±0.01 d	0.87 ±0.01 ab	2.81 ±0.01 b	0.66 ±0.01 c	1.94 ±0.01 c
Plateau	76.76 ±0.03 f	0.92 ±0.01 f	0.43 ±0.01 e	0.71 ±0.01 e	0.49 ±0.01 d	0.28 ±0.01 f
Rise	88.87 ±0.23 a	1.93 ±0.05 a	0.90 ±0.02 a	3.22 ±0.01 a	1.03 ±0.04 a	2.32 ±0.02 a
Sunrise	87.31 ±0.16 b	1.62 ±0.08 c	0.73 ±0.04 c	2.80 ±0.13 b	0.89 ±0.05 b	2.06 ±0.09 b

[a] Values are means ± standard deviations of three replicates. Means in the same column with different letters are significantly different ($p < 0.05$).

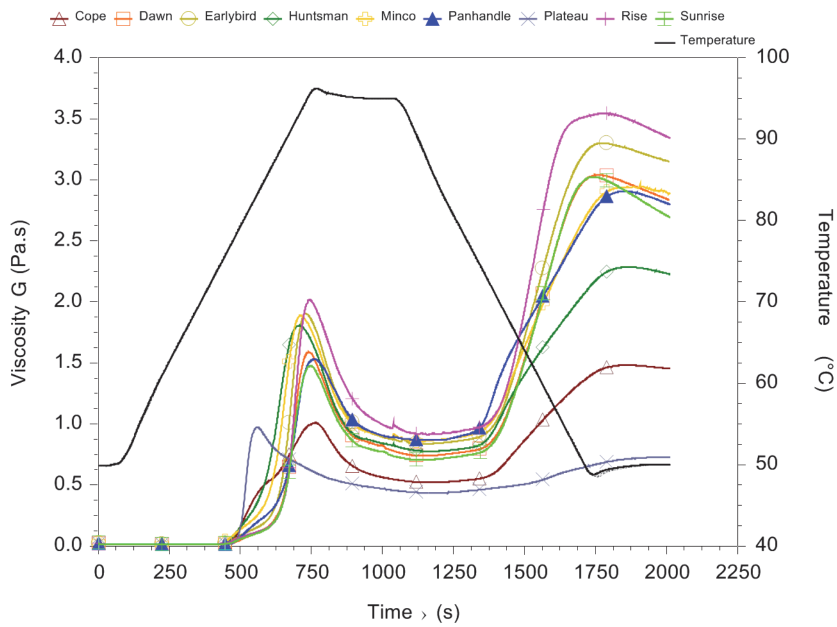

Figure 1. Pasting profiles of different proso millet cultivars.

waxy and medium amylose cultivars, indicating higher resistance to swelling (Singh et al., 2004).

Plateau had the lowest setback value of 0.28 Pa·s, while the medium amylose cultivar (*Cope*) had lower setback compared to the high amylose cultivars. The setback value reflects the degree of paste retrogradation. This is an indication that waxy millet will retrograde to a lesser extent as compared to cultivars with high amylose content. Three Korean proso millet cultivars, including waxy millet, showed similar setback and peak viscosity values (Kim et al., 2012).

Figures 2, 3, and 4 illustrate the strong positive correlations of amylose content with peak viscosity (r = 0.84), final viscosity (r = 0.91), and setback (r = 0.90), respectively. The pasting temperature and setback values were lower for *Plat-*

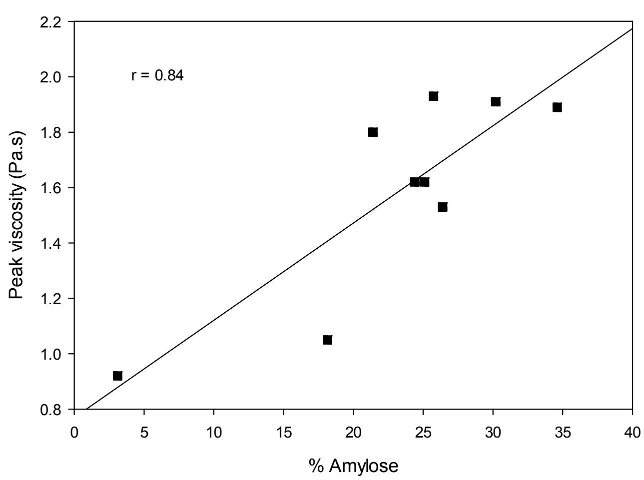

Figure 2. Relationship between % amylose and peak viscosity (Pa·s) for different proso millet cultivars.

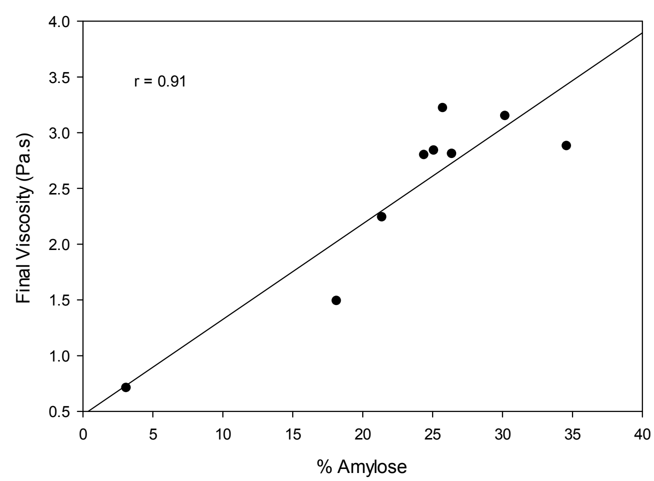

Figure 3. Relationship between % amylose and final viscosity (Pa·s) for different proso millet cultivars.

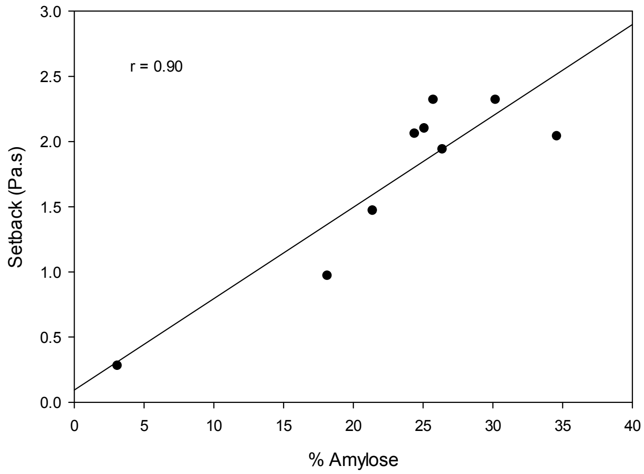

Figure 4. Relationship between % amylose and setback (Pa·s) for different proso millet cultivars.

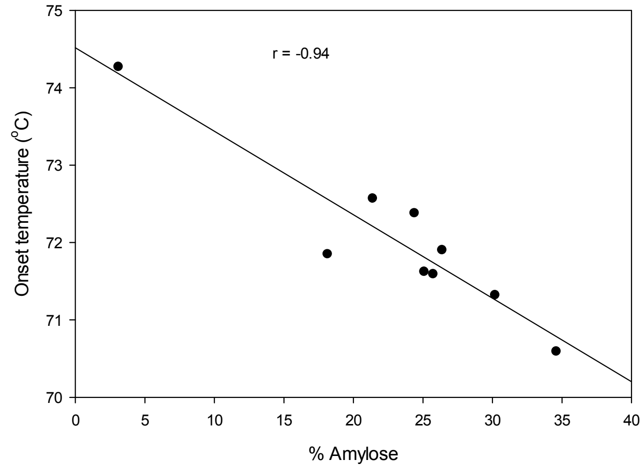

Figure 5. Relationship between % amylose and onset temperature (°C) for different proso millet cultivars.

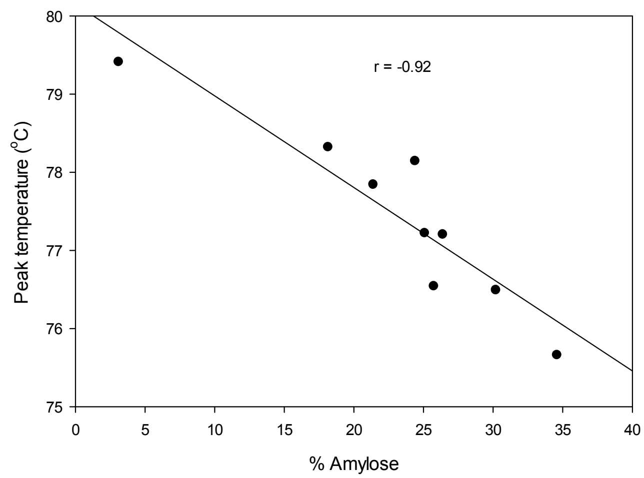

Figure 6. Relationship between % amylose and peak temperature (°C) for different proso millet cultivars.

eau and *Cope* than for the high amylose cultivars and are in accordance with results reported by Jane et al. (1999) for starches from different botanical sources. Wu et al. (2014) reported similar results for millet varieties grown in China and reported positive correlation of peak viscosity (r = 0.815), final viscosity (r = 0.890), and setback (r = 0.958) with amylose content.

Gelatinization Properties

The gelatinization properties of the proso millet cultivars are summarized in table 5. Significant differences ($p < 0.05$) in onset temperature (T_O), peak temperature (T_P), end temperature (T_C), and enthalpy (ΔH_G) were observed among the cultivars; T_O varied from 70.59°C (*Minco*) to 74.27°C (*Plateau*), T_P varied from 75.66°C (*Minco*) to 79.41°C (*Plateau*), and ΔH_G ranged from 2.38 J g^{-1} (*Sunrise*) to 3.45 J g^{-1} (*Plateau*).

The waxy millet (*Plateau*) had higher T_O and T_P than the other cultivars and showed a strong negative correlation of T_O (r = -0.94) and T_P (r = -0.94) with amylose content, as shown in figures 5 and 6, respectively. Waxy barley showed similar results for T_O, and higher T_P and ΔH_G were observed for waxy barley compared to non-waxy cultivars (Gudmundsson and Eliasson, 1992). Sasaki et al. (2000) and Yasui et al. (1996) also reported negative correlations between T_P, T_C, and ΔH_G and amylose content for wheat starches. Amylopectin plays an important role in starch granule crystallinity. With an increase in amylose content, the % crystallinity and the melting temperature of crystalline regions decrease, resulting in lower energy requirements for gelatinization (Sasaki et al., 2000). The negative correlation of amylose content with onset and peak temperatures indicates that higher amylose implies more amorphous regions and fewer crystalline regions. Wu et al. (2014) also reported higher T_P and ΔH_G for waxy millet compared to non-waxy millet for proso millet varieties grown in China.

Solubility and Swelling Power

A strong interaction between amorphous and crystalline regions was seen among the proso millet cultivars, as the

Table 5. Gelatinization properties of cultivars.[a]

Cultivar	Onset Temperature (°C)	Peak Temperature (°C)	End Temperature (°C)	ΔH_G (J g^{-1})	Range (°C)
Cope	71.85 ±0.01 c	78.32 ±0.17 b	91.80 ±0.49 ab	2.65 ±0.39 bcd	19.95 ±0.51 a
Dawn	71.62 ±0.02 cd	77.22 ±0.15 c	91.78 ±1.54 ab	2.51 ±0.22 bcd	19.17 ±2.93 a
Earlybird	71.32 ±0.01 d	76.49 ±0.12 d	88.95 ±0.60 c	2.41 ±0.08 cd	17.63 ±0.59 a
Huntsman	72.57 ±0.50 b	77.84 ±0.64 bc	91.92 ±0.17 ab	2.43 ±0.16 cd	19.36 ±0.33 a
Minco	70.59 ±0.01 e	75.66±0.15 e	89.38 ±1.84 c	2.91 ±0.36 b	17.79 ±3.26 a
Panhandle	71.90 ±0.28 c	77.20 ±0.14 c	92.13 ±0.58 ab	2.88 ±0.03 bc	20.23 ±0.30 ab
Plateau	74.27 ±0.09 a	79.41 ±0.01 a	92.53 ±1.58 ab	3.45 ±0.09 a	18.26 ±1.67 a
Rise	71.59 ±0.01 cd	76.54 ±0.15 d	90.19 ±0.18 bc	2.52 ±0.08 bcd	18.60 ±0.19 a
Sunrise	72.38 ±0.21 b	78.14 ±0.42 b	92.64 ±0.67 a	2.38 ±0.18 d	20.26 ±0.88 a

[a] Values are means ± standard deviations of three replicates. Means in the same column with different letters are significantly different ($p < 0.05$).

Table 6. Functional properties of cultivars.[a]

Cultivar	Water Binding Capacity (%)	70°C Solubility (%)	70°C Swelling (%)	80°C Solubility (%)	80°C Swelling (%)	90°C Solubility (%)	90°C Swelling (%)
Cope	236.92 ±0.70 a	6.95 ±0.49 b	8.12 ±0.48 ab	21.15 ±0.64 b	11.13 ±0.16 d	50.45 ±1.48 b	22.32 ±3.80 cd
Dawn	206.50 ±0.35 c	3.85 ±0.07 c	7.36 ±0.14 b	8.25 ±0.07 cd	14.14 ±0.77 bc	46.75 ±0.78 bc	30.36 ±3.20 ab
Earlybird	207.79 ±1.38 c	3.30 ±0.14 c	6.75 ±0.04 b	7.10 ±1.41 de	12.76 ±2.45 bcd	19.20 ±4.10 ef	21.65 ±2.03 cd
Huntsman	206.99 ±0.60 c	3.75 ±0.07 c	8.11 ±0.08 ab	7.05 ±0.21 de	13.17 ±0.86 bcd	23.50 ±2.97 de	26.00 ±1.77 bcd
Minco	224.87 ±1.10 b	4.05 ±0.21 c	8.35 ±0.29 ab	6.40 ±0.28 e	11.76 ±0.13 cd	42.30 ±4.81 c	27.56 ±1.64 abc
Panhandle	207.56 ±3.18 c	3.85 ±0.07 c	7.41 ±0.21 b	8.30 ±0.01 cd	14.19 ±0.70 bc	46.80 ±0.84 bc	30.41 ±3.12 ab
Plateau	235.49 ±1.85 a	15.00 ±2.97 a	9.86 ±3.01 a	61.65 ±0.07 a	23.73 ±0.92 a	70.35 ±4.31 a	24.67 ±2.29 bcd
Rise	201.95 ±1.46 d	4.60 ±0.14 c	7.86 ±0.09 ab	9.40 ±0.57 c	15.16 ±1.22 b	30.50 ±4.24 d	34.37 ±6.16 a
Sunrise	208.97 ±0.26 c	3.75 ±0.07 c	7.26 ±0.51 b	6.75 ±0.64 e	11.18 ±0.68 d	13.80 ±0.71 f	19.51 ±2.96 d

[a] Values are means ± standard deviations of three replicates. Means in the same column with different letters are significantly different ($p < 0.05$).

starches varied significantly in solubility and swelling power (table 6). The swelling power and solubility showed continuous increases with an increase in temperature, which is due to starch gelatinization, leading to irreversible changes in properties such as granular swelling, native crystallite melting, loss of birefringence, and starch solubilization (Collado and Corke, 2003). Heating of an aqueous suspension of starch causes disruption in the crystalline structure, and water molecules become linked with exposed hydroxyl groups of amylose and amylopectin through hydrogen bonding, resulting in swelling of the starch molecules and increased solubility as some soluble starch leaches into the liquid (Collado and Corke, 2003). The waxy starch (*Plateau*) had highest solubility and swelling power compared to the high amylose cultivars. *Sunrise* consistently had the lowest solubility and swelling power, and the solubility doubled with every 10°C rise in temperature.

Water Binding Capacity

Water binding capacity (WBC) is the tendency of starch granules to absorb water and the degree of association of water molecules within starch granules (Amoo et al., 2014). The WBC results are presented in table 6. Starches from *Cope* and *Plateau* had the highest WBC values of 236.92% and 235.49%, respectively, among all the cultivars. Apparently, these proso millet cultivars had the greatest amylopectin starch contents, implying that they contain waxy starch (table 1). High WBC can be exploited for delayed gelatinization in order to delay retrogradation (Kalita et al., 2014). No significant variations ($p > 0.05$) were observed in the WBC of the high amylose cultivars except for *Rise*, which was significantly different ($p < 0.05$) from the other cultivars, which might have been due to several factors, including the size, shape, and hydrophilic-hydrophobic balance of the starch granules as well as the pH, solubility, lipids, and carbohydrates associated with proteins and the thermodynamic properties of the starch granules (Shimelis et al., 2006).

Conclusion

The physical characteristics, including sphericity, volume, surface area, equivalent diameter, bulk and solid densities, porosity, angle of repose, hardness, weight, and color, of nine proso millet cultivars were determined, and significant ($p < 0.05$) differences were observed among them. Functional properties, such as swelling power and solubility, showed variations among the cultivars, and significant ($p < 0.05$) changes with increased temperature were observed. The cultivar effect was not significant ($p > 0.05$) for WBC except for *Plateau*, *Cope*, and *Rise*. Strong positive correlations of amylose content with peak viscosity ($r = 0.84$), final viscosity ($r = 0.91$), and setback ($r = 0.90$) were observed. Negative correlations of onset temperature ($r = -0.94$) and peak gelatinization temperature ($r = -0.92$) with amylose content were observed. These elucidated postharvest and functional properties of different proso millet cultivars will allow proper design of equipment and systems for processes such as sorting, drying, heating, cooling, and milling.

Acknowledgements

The information reported in this article (No. 16-05-106) is a project of the Kentucky Agricultural Experiment Station and is published with the approval of the Director. The work was supported by the USDA National Institute of Food and Agriculture, Multistate Project No. 1007893.

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