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Determination of physico-mechanical properties of African mesquite (*Prosopis africana*) seeds for the design and development of processing machines

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Abstract

The physico-mechanical properties of African Mesquite seeds were investigated for the purpose of designing and developing a suitable equipment necessary for processing the seeds of this biomaterial. The physical properties were determined at the moisture content of 13% dry basis while the mechanical properties were determined at different moisture contents of 13%, 16%, 18% and 21% dry basis. The mean seed length, width and thickness were found to be 9.98, 6.80 and 4.66 mm, respectively. The average arithmetic and geometric mean diameters were 7.26 and 6.82 mm, respectively. The mean surface area, projected area and volume were 149.27 mm^2, 58.16 mm^2 and 175.69 mm^3, respectively. The average roundness, sphericity and aspect ratio were 0.59, 0.63 and 0.64, respectively. The mean thousand grain mass, bulk density, true density and porosity were 335.80 g, 728.50 kg m^{-3}, 1126.63 kg m^{-3} and 34.50%, respectively. The mean static angle of repose was 36.33 Degrees. The static coefficients of friction were 0.64, 0.60, 0.58, 0.63 and 0.66 on mild steel, stainless steel, glass, plastic and plywood surfaces, respectively. The results of mechanical properties determined at different moisture contents do not show any specific trend with moisture content and had maximum force at peak, force at yield and force at break of 1054.567±98.329 N, 1025.633±142.302 N and 918.900±137.238 N, respectively. There were no limitations to the report. These parameters will serve as inputs for the efficient design of processing machines for African Mesquite seeds.

Keywords: African Mesquite; Physical; Mechanical; Moisture Content

1. Introduction

African mesquite (*Prosopis africana*) also known as iron tree is the only species of Prosopis that is indigenous to tropical Africa. Its tree could be between 4-20m long. This tree is characterized by a deep, fast-growing tap root. African Mesquite is perennial tree crop that grows as tall as 27 feet. *Prosopis africana* has vast social, economic, cultural, medicinal and agricultural values. The entire parts of *Prosopis africana* ranging from the roots to the leaves have been found to be beneficial to mankind in so many ways. Almost all the parts of the tree can be used for medicinal purposes. The leaves in particular are used for the treatment of headache, toothache, as well as other head ailments. The leaves and bark are combined to treat rheumatism while fishermen use the pounded dry fruit as fish poison (Akaaimo and Raji, 2006). The young leaves and shoots are used as fodder; cattle also like to eat the pods. The wood has a high thermal value of about 1720J/kg and produces excellent charcoal and firewood. Therefore, it can be used as a fuel as well. The bark and root can be used as tannin or dye stuff and the pod ashes are a source of potassium for making soap used to treat skin disease, fevers and as eye washes. The seeds are widely used and consumed in the entire country and beyond. The seeds are fermented to produce food condiments consumed by many people while its gum is used in the medical industry (Adikwu *et al.*, 2001). It is very popular for its seeds, highly priced food condiment or seasoning, rich in protein,

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fatty acids and other vital nutrients and minerals (Amusa *et al*., 2010; Ayanwuyi *et al*., 2010). The seeds are processed in the same way as locust bean seeds.

In spite of the economic importance of the African seed, there exists a dart of information about its physical and mechanical properties that could be used to design machines required for processing the seed. Similarly in the opinion of Asoiro and Ohagwu (2017), despite the huge importance, high consumption rate and the potential use of *Prosopis africana*, as a good source of foreign earnings for Nigeria, the traditional method of post-harvest processing provides a poor-quality product with low nutrient content. This has limited its utilization both locally and internationally. In Nigeria, there is scarcely any large-scale producer of *Prosopis africana* that use machinery for its storage, handling or processing. Many small-scale producers carry out these operations manually. Therefore, the mechanization of its processing has generated lots of interest in the recent time. To actualize its mechanization, it is therefore, necessary to establish some of its prominent engineering properties. The knowledge of these properties of the seed would go a long way in the design and construction of any agricultural machinery either during preservation or processing. Therefore, this work is carried out to determine the physico-mechanical properties of *Prosopis africana* seeds relevant to the design and development of processing machines.

Successful studies into physio-mechanical properties of *Prosopis africana* seeds will provide necessary and available data for the design of seeds processing machines; therefore, it is a step in the right direction towards mechanizing the processing of the seed. By extension, this may result into increased production of African mesquite by farmers, which translates into improved incomes for farmers and processors. To the agro-allied and pharmaceutical industries, mechanized activities in African mesquite seeds processing, could translate into increase in raw materials, there by guaranteeing year-round operations/functionality of those industries. It may have positive effects on the foreign exchange resulting from the export of processed seeds and other bye- products from the seeds, in Nigeria.

2. Materials and methods

2.1. Sample Preparation

Prosopis africana seeds used in this study were purchased from a market in Iware, Ardo-Kola Local Government Area of Taraba State, Nigeria. The seeds were cleaned manually to remove all foreign materials such as stones, immature and broken seeds. The sample was then poured into a polyethylene bag and the bag was tightly sealed. Hundred seeds were selected at random from the lot and their physical and mechanical properties were determined. The physical properties of *Prosopis africana* seeds were determined at the Department of Agricultural and Bioresources Engineering, Taraba state university, Jalingo, while the mechanical properties were determined at National Centre for Agricultural Mechanization (NCAM) Idofian Ilorin, Kwara State.

2.2. Moisture Content Determination

The initial moisture contents of the seeds were determined using the standard hot air oven method at 105 $^oC\pm1\ ^oC$ for 24 hours till there were no more changes in the weight. The initial moisture content (Dry basis) was obtained using Equation 1 (Mirzabe *et al*., 2016).

$$M_c = \frac{W_1 - W_2}{W_2} (\%) \quad \ldots\ldots\ldots\ldots\ldots(1)$$

Where; M_c = Moisture content (%), W_1 = Weight of seed before oven drying (g), W_2 = Weight of seed after oven drying (g).

2.3. Determination of Physical Properties of *Prosopis africana* Seeds

The physical properties of *Prosopis africana* seeds determined includes; dimensional properties, gravimetric properties and frictional properties.

2.3.1. Determination of dimensional properties

A Mitutoyo absolute digimatic vernier caliper with 0.001 mm accuracy was used to measure the Length (major diameter), Width (intermediate diameter) and Thickness (minor diameter) of the seeds. The average of each measurement was taken as the reading for each of the samples (Dauda *et al*., 2015; Balami *et al*., 2016).

- **Arithmetic mean diameter:** The arithmetic mean diameter (Da) of the seed was calculated using Equation 2 (Baryeh, 2002).

$$D_a = \frac{L+W+T}{3} \quad (mm) \quad \ldots\ldots\ldots\ldots (2)$$

- **Geometric mean diameter:** The geometric mean diameter (Dg) was determined from Equation 3 (Baryeh, 2002).

$$D_g = (LWT)^{\frac{1}{3}} \quad (mm) \quad \ldots\ldots\ldots\ldots (3)$$

- **Surface area of seeds:** The surface area (Sa) was obtained from Equation 4 given by Baryeh (2002).

$$S_a = \pi D_g^2 \quad (mm2) \quad \ldots\ldots\ldots\ldots (4)$$

- **Projected area:** The projected area (A_P) was determined using Equation 5 (Mirzabe *et al*., 2013).

$$A_P = \frac{\pi WL}{4} \quad (mm2) \ldots\ldots\ldots\ldots (5)$$

- **Volume of seeds:** The volume (V) of seeds was determined using Equation 6 (Mohsenin, 1987).

$$V = \frac{\pi}{6} LWT \quad (mm3) \quad \ldots\ldots\ldots\ldots (6)$$

- **Roundness:** The roundness (R) was determined from Equation 7 (Baryeh, 2002).

$$R = \frac{\left(\frac{W}{L} + \frac{T}{L} + \frac{T}{W}\right)}{3} \quad \ldots\ldots\ldots\ldots (7)$$

- **Sphericity:** The sphericity (ϕ) was determined from Equation 8 given by Baryeh (2002).

$$\emptyset = \frac{D_g}{L} \quad \ldots\ldots\ldots\ldots (8)$$

- **Aspect ratio of seeds:** The aspect ratio (Ra) was calculated from Equation 9 (Omobuwajo *et al*., 2000).

$$R_a = \frac{W}{L} \quad \ldots\ldots\ldots\ldots (9)$$

2.3.2. Determination of gravimetric properties

Thousand-grain weight: The 1000-unit mass (M1000) was determined using mettle electronic balance of accuracy of 0.001g. One-thousand-unit grains were carefully counted out from a cleaned sample of the grains and weighed in the balance. The measurements were replicated ten times (Sirisomboon *et al*., 2007).

Bulk density: The bulk density of the seeds was determined by filling a test tube of 20mL volume with the seeds and the content weighed using an electronic balance of 0.001g sensitivity. The measurements were replicated ten times (Garnayak *et al*., 2008). The bulk density was calculated from the mass of the kernels and the volume of the container from Equation 10 (Garnayak *et al*., 2008).

$$\rho_b = \frac{M_1 - M_2}{V} \quad (Kg\ m^{-3}) \quad \ldots\ldots\ldots\ldots (10)$$

Where; ρb= bulk density (Kg m^{-3}), M_1 = mass of filled container (Kg), M_2 = mass of empty container (Kg) and V =Volume of container (m^3).

True density: The true density of the seeds was determined by water displacement method as described by Mohsenin (1987). 50mL of distilled water was taken in a 100mL measuring jar and pre-weighed grains was filled inside the jar and the change in the level of water in the measuring jar was recorded. The experiment was done as snappy as possible to minimize the absorption of water by the seeds. The measurements were replicated ten times. The true density was calculated as the ratio of the mass of seeds to the volume of water displaced as in Equation 11 (Pradhan *et al*., 2013).

$$\rho_t = \frac{M}{V} \text{ (Kg m}^{-3}\text{)} \qquad \ldots\ldots\ldots\ldots (11)$$

Where; ρt = true density (Kg m-3), M = mass of seeds (Kg) and V = volume of water displaced (m3).

Porosity: Porosity (ρo) is defined as the fraction of space in the bulk grain, which is not occupied by grain. Equation 12 was used to obtain the porosity (Mohsenin, 1987).

$$P = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \quad (\%)\ldots\ldots\ldots\ldots (12)$$

2.3.3. Determination of frictional properties

Angle of repose: This was determined by using an open-ended cylinder of 15 cm diameter and 30 cm height. The cylinder was placed at the centre of circular plate having a diameter of 70 cm and was filled with grains, tapping during filling were done to obtain uniform packing. The cylinder was raised slowly until it formed a cone on the circular plate. The height H of the cone was recorded. The angle of repose (θ) was calculated using Equation 13 (Umogbai, 2009; Davies, 2009).

$$\theta = \tan^{-1}\left(\frac{2H}{D}\right) \quad \text{(Degrees)} \ldots\ldots\ldots\ldots (13)$$

Where; θ = angle of repose (O), H = vertical height of conical heap of grains (mm) and D = the diameter of base of cone formed (mm).

Coefficient of static friction: The coefficient of static friction for seed was determined against different surfaces using the inclined plane method. This involves placing the seeds on adjustable tilting surface equipment with the surface formed using different material surfaces. Manually, the inclination of the plate was increased gradually until the specimen starts to slide down and at that point, the angle of tilt in degree was read on a graduated scale (protractor). The angle of inclination with the horizontal was measured by a scale provided and was taken as an angle of friction and tangent of the angle was taken as coefficient of friction between surface and grains as in Equation 14 (Umogbai, 2009).

$$\mu = \tan\theta \ldots\ldots\ldots\ldots (14)$$

Where; μ = coefficient of static friction (dimensionless) and θ = angle of inclination of material surface (0).

2.3.4. Determination of Mechanical Properties of Prosopis africana Seeds

All compression tests were performed using Laboratory Testometric Micro 500 Universal Testing Machine at the National Centre for Agricultural Mechanization (NCAM), Ilorin Kwara State of Nigeria. The machine has an accuracy of 0.1kN and a maximum capacity of 50kN. Also, it has two standard test speeds, the lower 2.0mm/min and the higher 5.0mm/min for uni-axial compression tests on all biomaterials of convex shape. For the purposes of this research, it was only the maximum speed of 5.0mm/min that was used to determine the force-deformation parameters of African Mesquite at the intermediate axis. African Mesquite whose diameters were already determined physically were loaded individually using a laboratory thumb on the compression jaws or grips, the load cell sends the pressure transmitted to the console was sand witched between the lower jaw and the cross head which were driven by a screw press. When the upper jaw was lowered well enough to grip the samples, the laboratory thumb was withdrawn and the start button was pressed to commence the test. Compression force was exerted and the biomaterial failed as it was accompanied by a "crack sound" and a corresponding drop on the force-deformation curve which was plotted concurrently on the Personal Computer monitor when the sample thus failed the "end test" button was pressed on the console. The experimental procedure was repeated with 50 seeds maintaining the speed of 5.0mm/min.

2.3.5. Data Analysis

The preliminary experimental data that was processed involve the determination of the minimum, maximum, mean and standard deviation values of the physico-mechanical properties using Microsoft Excel 2016.

3. Results and discussion

3.1. Physical Properties

The result of the physical properties of African Mesquite (*Prosopis africana*) at 13% moisture content (w.b.), is presented in Table 1.

3.1.1. Dimensional properties

The results obtained from the seed size analysis (Table 1) show that the length ranged from 8.04 mm to 11.93 mm, with a mean value of 9.98 mm, the width varied from 5.10 mm to 8.50 mm with an average value of 6.80 mm. The thickness spread between 3.22 mm and 6.10 mm with mean value of 4.66 mm. The arithmetic mean diameter ranged from 6.15 mm to 8.37 mm with mean value of 7.26 mm, the geometric mean diameter was in the range of 5.83 mm to 7.82 mm with mean of 6.82 mm. The surface area of the seeds ranged from 106.57 mm2 to 191.96 mm2 with a mean value of 149.27 mm2, the projected area varied from 37.58 mm2 to 78.74 mm2 with mean value of 58.16 mm2 and the volume of seeds ranged from 102.82 mm3 to 248.55 mm3 with an average value of 175.69 mm3. The size and shape of seed determine the clearance between beaters (or hammers) and screen as found in separating and reduction machines. If the beater-screen clearance is larger than the seed, efficiency of the machine is largely reduced. If the clearance is smaller than seeds' size and shape, there will be losses due to seed breakage. The surface area is a function of the geometric diameter which is also dependent on the axial dimensions of the seed. The surface area of a grain is generally indicative of its pattern of behavior in a flowing fluid such as air, as well as the ease of separating extraneous materials from the grain during cleaning by pneumatic means (Omobuwajo *et al*., 2000).

The results obtained from the seed shape analysis (Table 1) show that the roundness of the seed ranged from 0.44 to 0.74 with a mean value of 0.59, the sphericity was in the range of 0.50 to 0.76 with an average value of 0.63 and the aspect ratio varied from 0.45 to 0.82 with a mean value of 0.64. Garnayak *et al*. (2008) considered any grain, fruit and seed as spherical when the sphericity value is above 70%, thus, the high sphericity of the soya bean seeds is indicative of the shape towards being a sphere. The lower sphericity values thus suggest that the kernels tend towards a cylindrical shape (Omobuwajo *et al*., 2000). The aspect ratio is an indicator of a tendency toward an oblong shape (Heidarbeigi *et al*., 2009). Thus, the lower values of the aspect ratio and sphericity generally indicate a likely difficulty in getting the kernels to roll than that of peas like spheroid grains. They can, however, slide on their flat surfaces. This tendency to either roll or slide should be necessary in the design of hoppers for milling process.

3.1.2. Gravimetric properties

The results obtained from the analysis of the gravimetric properties of the seeds (Table 1) show that the thousand grain mass of the African mesquite (*Prosopis africana*) seeds varied from 268.15 g to 392.43 g with mean value of 335.80 g, the tapped bulk density varied from 662.47 kg m-3 to 801.92 kg m-3 with mean value of 728.50 kg m-3, the true density values were in the range of 1098.26 kg m-3 to 1213.54 kg m-3 with mean value of 1126.63 kg m-3 and the porosity value of the seeds ranged from 28.66% to 44.12% with a mean value of 34.50%. The value of true density indicates that, the kernel density is higher than water, which is the important property in case of food grains during wet cleaning, as kernels do not float on water. The densities are useful in the theoretical calculation of the capacity of processing machines. The property of porosity is required in air and heat flow in agricultural material. This shows how easily a stream of heated air for drying will pass through a pack of material and thus affect the rate of drying of the material.

3.1.3. Frictional properties

The results obtained from the analysis of the frictional properties of the seeds (Table 1) show that the static angle of repose of the African mesquite (*Prosopis africana*) seeds varied from 34.82o to 38.74o with mean value of 36.33o. The static coefficient of friction of the African mesquite (*Prosopis africana*) seeds obtained from different material surfaces varied from 0.62 to 0.68 with a mean value of 0.64 on mild steel surface, ranged from 0.57 to 0.65 with a mean value of 0.60 on stainless steel surface, varied from 0.54 to 0.63 with a mean value of 0.58 on glass surface, ranged from 0.61 to 0.67 with a mean value of 0.63 on plastic surface and varied from 0.63 to 0.71 with a mean value of 0.66 on plywood surface. Generally, plywood surface was surprisingly observed to offer some resistance to sliding to the seeds of African mesquite (*Prosopis africana*). Though the size and weight of seeds, as well as the packing differences of seeds and surface characteristics of each of the structural surfaces used (even at the microscopic level) may have resulted in the degrees of disparities observed in the values of the coefficient of static friction. This observation may make a case for using less expensive, natural sources of contact surfaces when selecting and determining the slopes of the feed hopper of African mesquite (*Prosopis africana*) seed processing equipment, or in the design of seed hopper in mechanized planters.

Table 1 Physical Properties of African Mesquite (*Prosopis africana*)

Physical Properties	**Unit**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
Dimensional Properties					
Length	mm	8.04	11.93	9.98	0.82
Width	mm	5.10	8.50	6.80	0.70
Thickness	mm	3.22	6.10	4.66	0.56
Arithmetic mean dia.	mm	6.15	8.37	7.26	0.48
Geometric mean dia.	mm	5.83	7.82	6.82	0.48
Surface area	mm^2	106.57	191.96	149.27	20.14
Projected area	mm^2	37.58	78.74	58.16	7.65
Volume	mm^3	102.82	248.55	175.69	33.90
Roundness		0.44	0.74	0.59	0.05
Sphericity		0.50	0.76	0.63	0.05
Aspect ratio		0.45	0.82	0.64	0.08
Gravimetric Properties					
Thousand grain mass	g	268.15	392.43	335.80	28.04
Bulk density	kgm^{-3}	662.47	801.92	728.50	24.53
True density	kgm^{-3}	1098.26	1213.54	1126.63	17.14
Porosity	%	28.66	44.12	34.50	3.46
Frictional Properties					
Static angle of repose	Degrees	34.82	38.74	36.33	2.21
Static coefficient of friction on:					
Mild steel		0.62	0.68	0.64	0.02
Stainless steel		0.57	0.65	0.60	0.01
Glass		0.54	0.63	0.58	0.03
Plastic		0.61	0.67	0.63	0.03
Plywood		0.63	0.71	0.66	0.01

3.2. Mechanical properties

The result of the mechanical properties of African Mesquite (*Prosopis africana*) at different moisture content is shown in Table 2.

According to the results (Table 2), the force, deformation, strain, stress and energy for African mesquite (*Prosopis africana*) seeds do not show any specific trend with moisture content. The highest force at peak (1054.567±98.329 N) was obtained at 16% moisture content while the lowest force at peak (857.300±202.719 N) was obtained at 21% moisture content, the highest deformation at peak (3.327±1.245 mm) was obtained at 21% moisture content while the lowest deformation at peak (2.046±0.150 mm) was obtained at 16% moisture content, the highest strain at peak (9.395±3.517%) was obtained at 21% moisture content while the lowest strain at peak (5.845±0.428%) was obtained at 16% moisture content, the highest stress at peak (6.714±5.300 N mm^{-2}) was obtained at 18% moisture content while the lowest stress at peak (3.053±0.734 N mm^{-2}) was obtained at 21% moisture content and the highest energy at peak (1.671±0.668 Nm) was obtained at 13% moisture content while the lowest energy at peak (1.091±0.250 Nm) was obtained at 16% moisture content.

Table 2 Mechanical Properties of African Mesquite (*Prosopis africana*) Seeds

Properties	Moisture Content			
	13% (db)	**16% (db)**	**18% (db)**	**21% (db)**
Force at Peak (N)	1027.967±143.033	1054.567±98.329	875.467±292.547	857.300±202.719
Deformation at Peak (mm)	3.087±0.616	2.046±0.150	2.727±0.407	3.327±1.245
Strain at Peak (%)	6.971±1.391	5.845±0.428	7.167±1.069	9.395±3.517
Stress at Peak (N/mm^2)	4.111±1.854	5.819±1.110	6.714±5.300	3.053±0.734
Energy at Peak (N.m)	1.671±0.668	1.091±0.250	1.163±0.384	1.460±1.024
Force at Yield (N)	1025.633±142.302	1020.100±94.922	875.467±292.547	772.500±101.676
Deformation at Yield (mm)	3.025±0.666	1.825±0.403	2.727±0.407	2.736±0.344
Strain at Yield (%)	6.831±1.504	5.213±1.150	7.167±1.069	7.728±0.971
Stress at Yield (N/mm^2)	4.101±1.851	5.673±1.347	6.714±5.300	2.754±0.430
Energy at Yield (N.m)	1.606±0.722	0.861±0.170	1.163±0.384	0.929±0.190
Force at Break (N)	918.900±137.238	848.300±255.261	519.553±197.313	787.700±276.609
Deformation at Break (mm)	3.362±0.889	2.974±0.900	3.332±0.470	3.586±1.105
Strain at Break (%)	7.592±2.006	8.497±2.572	8.757±1.235	10.128±3.120
Stress at Break (N/mm^2)	3.779±1.875	4.842±2.103	3.707±2.360	2.807±0.992
Energy at Break (N.m)	1.952±0.980	1.806±0.922	1.559±0.367	1.636±0.906

The highest force at yield (1025.633±142.302 N) was obtained at 13% moisture content while the lowest force at yield (772.500±101.676 N) was obtained at 21% moisture content, the highest deformation at yield (3.025±0.666 mm) was obtained at 13% moisture content while the lowest deformation at yield (1.825±0.403 mm) was obtained at 16% moisture content, the highest strain at yield (7.728±0.971%) was obtained at 21% moisture content while the lowest strain at yield (5.213±1.150%) was obtained at 16% moisture content, the highest stress at yield (6.714±5.300 N mm^{-2}) was obtained at 18% moisture content while the lowest stress at yield (2.754±0.430 N mm^{-2}) was obtained at 21% moisture content and the highest energy at yield (1.606±0.722 Nm) was obtained at 13% moisture content while the lowest energy at yield (0.861±0.170 Nm) was obtained at 16% moisture content.

The highest force at break (918.900±137.238 N) was obtained at 13% moisture content while the lowest force at break (519.553±197.313 N) was obtained at 18% moisture content, the highest deformation at break (3.586±1.105 mm) was obtained at 21% moisture content while the lowest deformation at break (2.974±0.900 mm) was obtained at 16% moisture content, the highest strain at break (10.128±3.120%) was obtained at 21% moisture content while the lowest strain at break (7.592±2.006%) was obtained at 13% moisture content, the highest stress at break (4.842±2.103 N mm-2) was obtained at 16% moisture content while the lowest stress at break (2.807±0.992 N mm^{-2}) was obtained at 21% moisture content and the highest energy at break (1.952±0.980 Nm) was obtained at 13% moisture content while the lowest energy at break (1.559±0.367 Nm) was obtained at 18% moisture content.

4. Conclusion

Having carried out investigations on some physical and mechanical properties of the *Prosopis africana* seed, the results of the test has shown good agreement with some of the general trend and ranges obtained for other similar crops. The distinctive shapes and sizes of the seeds as identified by the values of sphericity and then size distribution pattern can be effectively utilized for the selection of sizes and shapes of screens that can be employed in mechanical separation of seeds and hence will make the process of mechanization in size reduction, separation and cleaning very easy. The seed being very hard and non-porous indicates that there is a need for pre-treatment before processing and handling especially dehulling. The properties are also a good data source useful in the design and development of the necessary processing machines for the crop. This will help in using appropriate data rather than using properties of similar crops in machine and process design for *P. Africana* seed.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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