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Research Article

Effects of Harvesting Times and Germplasm Accessions on the Physical Properties of Roselle (*Hibiscus sabdariffa* L.) Seeds

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Roselle (*Hibiscus sabdariffa* L.) is an important crop grown successfully in tropical and subtropical climates with huge nutritional, economic, and industrial benefits. The physical properties of seeds, particularly length, width, thickness, mean diameter, angle of repose, degree of sphericity, mass, and surface area, have been found to play significant roles in designing equipment for storage, transportation, and subsequent field operations of the seeds. Therefore, a study was carried out to determine the effects of different harvesting times on the physical properties of seeds of twelve roselle accessions for their subsequent industrial management. In total, 12×3 factorial arrangements in Randomized Complete Block Design and Completely Randomized Design were used for the field and laboratory experiments, respectively. The first factor was germplasm accessions at twelve levels (HS08, HS11, HS19, HS25, HS27, HS32, HS41, HS58, HS59, HS69, HS83, and H86), and the second factor was harvesting times at three levels (physiological maturity, one week after physiological maturity, and two weeks after physiological maturity). Seeds of accession HS32 harvested at the physiological maturity stage had the highest moisture content, which was similar to the other 11 accessions harvested at the same stage. The seeds of accession HS08 harvested at physiological maturity had significantly the best values in seed length (4.33 mm), seed width (4.30 mm), seed thickness (2.43 mm), seed geometric mean diameter (3.83 mm), seed angle of repose (20.57°), seed sphericity (0.76), seed surface area (18.57 mm^2), and seed mass (0.05 g). Further, there were strongly positive and significant correlations between seed width and seed angle of repose ($r = 0.93$); seed width and seed length ($r = 0.84$); seed width and mean seed diameter ($r = 0.89$); seed width and seed sphericity ($r = 0.68$); seed width and seed surface area (0.94). There were also strongly positive and significant correlations between seed thickness and seed sphericity ($r = 0.79$) and also between seed thickness and seed surface area ($r = 0.63$). In conclusion, the physical properties of accession HS08 harvested at the physiological maturity stage could be very important in designing machinery for roselle seeds storage, transportation, and subsequent field operations.

1. Introduction

Roselle (*Hibiscus sabdariffa* L.) is a short day, annual herbaceous, bast fiber-bearing plant belonging to the Malvaceae family. *Hibiscus*, as a genus, has more than three hundred species distributed in tropical and subtropical regions around the world and are used as ornamental plants. However, the *sabdariffa* species is the most economically important member of the genus *Hibiscus* in terms of fiber production [1]. In addition to its use as fiber, various parts of roselle have been utilized as food and also in traditional medicine for the prevention of diseases such as diabetes, cancer, hypertension, and obesity [2]. The juice produced from the roselle leaves is rich in vitamins A, B, and C, iron, phosphorous, anthocyanins, and thiocene, which help in reducing high blood pressure, strengthening the heart, and reducing blood viscosity [3]. Roselle also contains antioxidants which are important in treating some cancerous tumors [4]. The bast fiber obtained from roselle has provided substantial wealth in India, Southeast Asia, Russia, Kenya, Nigeria, Sudan, Italy, and Côte d'Ivoire [5, 6]. In addition, the oil extracted from the seeds is used for cooking, soap making, and cosmetics, while the residue is used for feeding chicken and livestock [7].

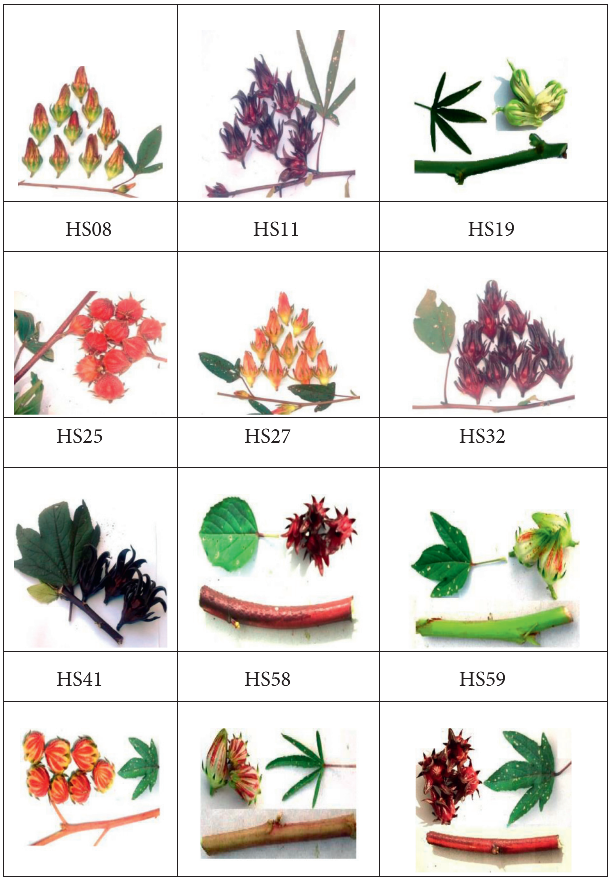

Figure 1: Pictorial presentation of the selected twelve distinctly different accessions.

The stage of maturity at harvest is one of the most important factors that can influence the quality of seeds [8]. Harvesting too early may result in low yield and quality because of the partial development of essential structures of seeds [9], whereas harvesting too late may increase the risk of shattering and decrease the quality of seeds due to ageing. In the postproduction management of crop seeds, the physical properties of the seeds have been found to play significant roles in designing equipment for the storage, transportation, and subsequent field operations of the seeds [10]. For instance, Eboibi and Eguru [11] reported that the stage at which the seeds of beans (*Phaseolus vulgaris*) was harvested influenced their physical properties and quality parameters and subsequently played a critical role in the design of harvesting, cleaning, grading, and separation equipment for the bean seeds. Araujo et al. [12] also reported the significant influence of the stage of harvesting on the physical properties of sesame (*Sesamum indicum*) seeds. For roselle seeds, few studies have reported on how different seed moisture variations affect their physical properties [13, 14]. However, no studies on the physical properties have been done in relation to the time of harvesting the seeds. The physical properties of interest include the seed surface area, seed length, seed width, seed thickness, seed degree of sphericity, seed mass, and seed angle of repose [15]. Therefore, the main objective of this study was to evaluate the effects of different harvesting times on the physical properties of seeds of twelve accessions of roselle, which could be important in the design of machinery for roselle seeds storage, transportation, and subsequent field operations.

2. Materials and Methods

2.1. Studies Location. The field and laboratory studies were conducted at the Department of Horticulture, KNUST, Kumasi, from June 2019 to January 2020. The site is in the semideciduous forest zone with an elevation of 186 m above sea level (ASL) and bimodal rainfall distribution. The major rainy season is from late March to mid-July. There is a short dry spell from mid-July to mid-September, followed by the minor rainy season from mid-September to mid-November. The mean annual rainfall was 1500 mm. The mean minimum and maximum temperatures were 21 °C and 31 °C, respectively. The mean annual relative humidity is 95% in the morning and about 60% at noon. The soil at the experimental site is Ferric Acrisol.

2.2. Accessions Seeds Collection, Preliminary Screening, and Selection. Seeds of twenty-five (25) different accessions were collected from roselle growing communities in the three Northern Regions and parts of the Bono Region of Ghana. The seeds were planted on the field, and a preliminary morphological characterization was done to establish the similarities or differences among the collected accessions. At the end of the characterization, twelve accessions (Figure 1), which were distinctly different from each other, were selected for the experimental studies.

2.3. Field Experimental Design and Crop Management. The field experiment was set up in a 12×3 factorial arrangement in Randomized Complete Block Design (RCBD) with three replications. The first factor was roselle accessions at twelve levels (HS08, HS11, HS19, HS25, HS27, HS32, HS41, HS58, HS59, HS69, HS83, and H86). The second factor was harvesting time at three levels (harvesting at physiological maturity; harvesting one week after physiological maturity; harvesting two weeks after physiological maturity). The experimental field was ploughed and harrowed, and plots measuring 3.6 m^2 each were demarcated. Seeds of the twelve accessions were planted in each designated plot at a spacing of 60 cm between rows and 30 cm within rows. There were six rows in each treatment plot. One-metre alleys separated the replicates, while 0.6 m separated the plots in each replicate. Three seeds were planted per hill and thinned to one plant at two weeks after planting (WAP). Weeds were effectively controlled during the growing period by hoe weeding at three-week intervals till harvesting was done. Insect pest control was carried out at 2 WAP, 6 WAP, and 10 WAP using Golan (acetamiprid as an active ingredient) at a rate of 1280 ml per 16 litres of water. Seeds of the accessions were harvested at the prescribed treatment times.

2.4. Laboratory Experimental Design for Determination of Seed Physical Properties. The physical properties of the seeds from the various treatment combinations (accessions *x* harvesting times) were determined in the laboratory using a 12×3 factorial arrangement in Completely Randomized Design (CRD) replicated four times.

Seed moisture content and seed physical properties of interest (seed length, seed width, seed thickness, seed surface area, seed angle of repose, seed geometric mean diameter, seed degree of sphericity, and 1000 seed mass) were determined.

2.4.1. Determination of Seed Moisture Content (%). The low constant temperature oven method was used to determine the moisture content of the seeds [16]. An empty glass crucible was thoroughly washed, cleaned, and dried for one hour at 130°C and placed in a desiccator to cool. The empty glass crucible and its cover were then weighed before filling with the sample. Moreover, 5 g of milled seed from each treatment sample was weighed and transferred into an empty crucible and placed in an oven to dry at a temperature of 105°C for 5 hours. At the end of the five hours, the crucible was covered, removed from the oven, and allowed to cool to room temperature in a desiccator. After cooling, the crucible with its cover and content of milled seed was reweighed and recorded. The difference in weight was noted, and the percentage moisture content of the seed sample was calculated using the following formula:

$$\%\ \text{seed moisture content} = \frac{(\text{weight of wet sample} - \text{weight of dry sample}) \times 100}{\text{weight of wet sample}}. \quad (1)$$

2.4.2. Measurement of Seed Length, Seed Width, and Seed Thickness (mm). One hundred roselle seeds were randomly selected from each treatment combination and labeled. The length, width, and thickness of each seed were measured with a micrometer (Mitutoyo Corporation, Japan) to an accuracy of 0.001 mm.

2.4.3. Determination of Seed Surface Area (mm^2). The surface area was determined using fifty (50) seeds and in accordance with the methods of Oje and Ugbor [17]. The surface of fifty seeds was first coated with blue paint and then imprinted on a light flexible paper with 0.01 mm thickness. The surface section was traced out with a very sharp thin pencil on graph paper. The surface area was measured by counting the number of squares on the graph paper within the traced area.

2.4.4. Angle of Repose of Seeds (^{0}). The dynamic angle of repose of seeds was determined using the method of Olaoye [18]. A specially constructed topless and bottomless box made of plywood measuring 450 mm × 450 mm × 450 mm with a removable front panel. The box was filled with one thousand roselle seeds from each treatment and placed on the floor. The front panel of the box was then quickly removed, allowing the seeds to slide down and assume a natural slope. The angle of repose was computed from the measurements of the height (x) of the free surface of the seeds and the diameter (y) of the heap formed outside the box using the following formula:

$$\text{angle of repose } \theta = \text{Tan}^{-1}\frac{x}{y}. \quad (2)$$

2.4.5. Geometric Mean Diameter (mm). One hundred seeds (100) were used. The seed geometric mean diameter (D_g) was computed using the formula of Mohsenin [19] as follows:

$$D_g = (LWT)^{1/3}, \quad (3)$$

where D_g is geometric mean diameter; L is length; W is width; T is thickness.

2.4.6. Degree of Sphericity. The degree of sphericity was determined using the method of Bamgboye and Adejumo [14]. One hundred seeds (100) were used and the accompanying formula as follows:

$$\Phi = (\text{LWT})^{1/3} L, \quad (4)$$

where Φ is the degree of sphericity; L is the length; W is the width; T is the thickness, 1000 seed mass (g).

Thousand seed weight was obtained using the digital weighing balance of 0.01 g accuracy.

3. Data Analysis

Data collected were subjected to analysis of variance (ANOVA) using Statistix version 10.0. Tukey's HSD (honestly significant difference) at a probability level of $p = 0.01$ was used for the mean separation of treatments. Pearson's correlation analyses were also performed on the data variables.

4. Results

4.1. Effects of Harvesting Times and Accessions on the Seed Moisture Content of Roselle. There were significant harvesting times *x* roselle accessions interactions ($p < 0.01$) for seed moisture content (Table 1). Seeds of accession HS32 harvested at the physiological maturity stage had the highest moisture, significantly different from most the treatment combinations, yet similar to those of the other accessions at the same physiological maturity stage. The least moisture content was recorded by seeds of the accessions harvested at two weeks after physiological maturity. Among the accessions, seeds of accessions HS32 had the highest moisture

Table 1: Interactive effects of harvesting times x accessions on the seed moisture content of roselle.

	Harvesting times			
Accessions	Physiological maturity	One week after physiological maturity	Two weeks after physiological maturity	Means
HS08	10.10	9.10	8.10	9.10
HS11	10.60	8.93	8.27	9.27
HS19	10.10	9.10	8.10	9.10
HS25	10.30	9.30	8.30	9.30
HS27	10.10	9.10	8.10	9.10
HS32	11.10	10.10	8.60	9.93
HS41	10.10	9.10	8.40	9.10
HS58	10.80	9.80	8.10	9.67
HS59	10.10	9.10	8.10	9.10
HS69	10.70	9.70	8.33	9.58
HS83	10.10	9.10	8.10	9.10
HS86	10.10	9.10	8.10	9.10
Means	10.35	9.29	8.22	
HSD (0.01): accessions = 0.531; harvesting times = 0.204; accessions x harvesting times = 1.054				

Table 2: Interactive effects of harvesting times x accessions on the seed length (mm) of roselle.

	Harvesting times			
Accessions	Physiological maturity	One week after physiological maturity	Two weeks after physiological maturity	Means
HS08	4.33	4.00	4.00	4.11
HS11	3.97	3.73	3.73	3.81
HS19	4.07	3.83	3.83	3.91
HS25	4.23	4.00	4.00	4.08
HS27	3.97	3.73	3.73	3.81
HS32	4.07	3.83	3.83	3.91
HS41	3.93	3.70	3.70	3.78
HS58	3.97	3.73	3.73	3.81
HS59	4.07	3.83	3.83	3.91
HS69	3.93	3.70	3.70	3.78
HS83	4.07	3.83	3.83	3.91
HS86	4.23	4.00	4.00	4.08
Means	4.07	3.83	3.83	
HSD (0.01): accessions = 0.300; harvesting times = 0.110; accessions x harvesting times = 0.100				

content, although similar to those of accessions H58 and HS69. The least moisture contents were found in seven other accessions (HS08, HS19, HS27, HS41, HS59, HS83, and HS86), yet similar to those of accessions HS11 and HS25. Between the harvesting times, seeds harvested at physiological maturity had the highest seed moisture content (10.35%), significantly different from those harvested at one week after physiological maturity (9.29%) and two weeks after physiological maturity (8.22%). The least moisture content was from seeds harvested at two weeks after physiological maturity (Table 1.)

4.2. Effects of Harvesting Times and Accessions on the Seed Length of Roselle. There were significant harvesting times x roselle accessions interactions ($p < 0.01$) for seed length (Table 2). Seeds of accession HS08, HS25, and HS86 harvested at the physiological maturity stage had the longest length (4.33 mm), significantly different from all the other treatment combinations. The shortest seed length was produced by seeds of accessions HS41 and HS69 harvested at both one and two weeks after physiological maturity. Among the accessions, the longest seed lengths were produced by seeds of accession HS08, although similar to those of accessions H19, HS25, H32, H59, H83, and HS86. The shortest seed lengths were produced by accessions HS41 and HS69 (Table 2). Between the harvesting times, seeds harvested at physiological maturity had the longest length, significantly different from those harvested at one and two weeks after physiological maturity, which had the least lengths (Table 2).

4.3. Effects of Harvesting Times and Accessions on the Seed Width of Roselle. There were significant harvesting times x roselle accessions interactions ($p < 0.01$) for seed width (Table 3). Seeds of accession HS08 harvested at the physiological maturity stage had the biggest width (4.30 mm) significantly different from all the other treatment combinations. The smallest seed width (3.57 mm) was produced by seeds of accessions HS11, HS27, and HS58 harvested at both one and two weeks after physiological maturity.

Among the accessions, the biggest seed width was produced by seeds of accession HS08, while the smallest seed width was by accessions HS11, HS27, and HS58 (Table 3).

Table 3: Interactive effects of harvesting times x accessions on the seed width (mm) of roselle.

	Harvesting times			
Accessions	Physiological maturity	One week after physiological maturity	Two weeks after physiological maturity	Means
HS08	4.30	3.77	3.77	3.94
HS11	3.87	3.57	3.57	3.67
HS19	3.97	3.67	3.67	3.77
HS25	4.07	3.77	3.77	3.87
HS27	3.87	3.57	3.57	3.67
HS32	3.97	3.67	3.67	3.77
HS41	3.97	3.67	3.67	3.77
HS59	3.97	3.67	3.67	3.77
HS58	3.87	3.57	3.57	3.67
HS69	3.97	3.67	3.67	3.77
HS83	3.97	3.67	3.67	3.77
HS86	4.07	3.77	3.77	3.87
Means	3.99	3.67	3.67	
HSD (0.01): sccessions = 0.260; harvesting times = 0.300; accessions x harvesting times = 0.112				

Table 4: Interactive effects of harvesting times x accessions on the seed thickness (mm) of roselle.

	Harvesting times			
Accessions	Physiological maturity	One week after physiological maturity	Two weeks after physiological maturity	Means
HS08	2.43	2.20	2.20	2.28
HS11	2.20	2.10	2.10	2.13
HS19	1.80	1.70	1.70	1.73
HS25	2.30	2.20	2.20	2.23
HS27	2.20	2.10	2.10	2.13
HS32	1.80	1.70	1.70	1.73
HS41	2.20	2.10	2.10	2.13
HS59	1.80	1.70	1.70	1.73
HS58	2.20	2.10	2.10	2.13
HS69	2.20	2.10	2.10	2.13
HS83	1.80	1.70	1.70	1.73
HS86	2.30	2.20	2.20	2.23
Means	2.10	1.99	1.99	
HSD (0.05): accessions = 0.450; harvesting times = 0.100; accessions x harvesting times = 0.211				

Among the harvesting times, seeds harvested at the physiological maturity stage had the biggest width, significantly different from those harvested at one and two weeks after physiological maturity, which had the lowest (Table 3).

4.4. Effects of Harvesting Times and Accessions on the Seed Thickness (mm) of Roselle. There were significant harvesting times *x* roselle accessions interactions ($p < 0.01$) for seed thickness (Table 4). Seeds of accession HS08 harvested at the physiological maturity stage had the greatest thickness (2.43 mm) significantly different from most the treatment combinations, yet similar to that of accession H86 at the same physiological maturity stage. The smallest seed thickness (1.70 mm) was produced by seeds of accessions HS19, HS32, HS59, and HS83 harvested at both one and two weeks after physiological maturity. Among the roselle accessions, the greatest seed thickness was produced by seeds of accessions HS08, while the smallest seed thickness was by accessions HS19, HS32, HS59, and HS83 (Table 3). Between the harvesting times, seeds harvested at the physiological maturity stage had the greatest thickness (2.10 mm), significantly different from those harvested at one and two weeks after physiological maturity (1.99 mm), which had the smallest thickness (Table 4).

4.5. Effects of Harvesting Times and Accessions on the Seed Geometric Mean Diameter (mm) of Roselle. There were significant harvesting times *x* roselle accessions interactions ($p < 0.01$) for seed geometric mean diameter (Table 5). Seeds of accession HS08 harvested at the physiological maturity stage had the biggest geometric mean diameter (3.83 mm) significantly different from all the other treatment combinations. The smallest geometric mean diameter (3.40 mm) was produced by seeds of accessions HS11, HS27, HS41, HS58, and HS69 harvested at both one and two weeks after physiological maturity. Among the roselle accessions, the biggest mean diameter (3.68 mm) was produced by seeds of accessions HS08, H25, and H86, while the smallest mean diameter (3.47 mm) was by HS11, HS27, HS41, H58, and HS69 (Table 5). Among the harvesting times, seeds harvested at

Table 5: Interactive effects of harvesting times x accessions on the seed geometric mean diameter (mm) of roselle.

Accessions	Harvesting times Physiological maturity	One week after physiological maturity	Two weeks after physiological maturity	Means
HS08	3.83	3.60	3.60	3.68
HS11	3.60	3.40	3.40	3.47
HS19	3.70	3.50	3.50	3.57
HS25	3.80	3.60	3.60	3.68
HS27	3.60	3.40	3.40	3.47
HS32	3.70	3.50	3.50	3.57
HS41	3.60	3.40	3.40	3.47
HS58	3.60	3.40	3.40	3.47
HS59	3.70	3.50	3.50	3.57
HS69	3.60	3.40	3.40	3.47
HS83	3.70	3.50	3.50	3.57
HS86	3.80	3.60	3.60	3.68
Means	3.69	3.48	3.48	

HSD (0.05): accessions = 0.200; harvesting times = 0.199; accessions x harvesting times = 0.02

Table 6: Interactive effects of harvesting times x accessions on the angle of repose (0) of roselle.

Accessions	Harvesting times Physiological maturity	One week after physiological maturity	Two weeks after physiological maturity	Means
HS08	20.57	19.91	19.91	20.13
HS11	19.90	19.70	19.70	19.77
HS19	20.10	19.90	19.90	19.97
HS25	20.11	19.91	19.91	19.98
HS27	19.90	19.70	19.70	19.77
HS32	20.10	19.90	19.90	19.97
HS41	20.00	19.80	19.80	19.87
HS59	20.10	19.90	19.90	19.97
HS58	19.90	19.70	19.70	19.77
HS69	20.00	19.80	19.80	19.87
HS83	20.10	19.90	19.90	19.97
HS86	20.11	19.91	19.91	19.98
Means	20.07	19.84	19.84	

HSD (0.05): accessions = 0.333; harvesting times = 0.111; accessions x harvesting times = 0.390

Table 7: Interactive effects of harvesting times x accessions on the 1000 seed mass (g) of roselle.

Accessions	Harvesting times Physiological maturity	One week after physiological maturity	Two weeks after physiological maturity	Means
HS08	0.04	0.04	0.04	0.04
HS11	0.03	0.03	0.03	0.03
HS19	0.03	0.03	0.03	0.03
HS25	0.04	0.04	0.04	0.04
HS27	0.03	0.03	0.03	0.03
HS32	0.03	0.03	0.03	0.03
HS41	0.05	0.05	0.05	0.05
HS58	0.03	0.03	0.03	0.03
HS59	0.03	0.03	0.03	0.03
HS69	0.05	0.05	0.05	0.05
HS83	0.03	0.03	0.03	0.03
HS86	0.04	0.04	0.04	0.04
Means	0.04	0.04	0.04	

HSD (0.05): accessions = 0.010; harvesting times = 0.010; accessions x harvesting times = 0.001

the physiological maturity stage had the biggest mean diameter (3.69 mm), significantly different from those harvested at one and two weeks after physiological maturity (3.48 mm), which had the least (Table 5).

4.6. Effects of Harvesting Times and Accessions on the Angle of Repose of Seed of Roselle. There were significant harvesting times x roselle accessions interactions ($p < 0.01$) for the seed angle of repose (Table 6). Seeds of accession HS08 harvested

Table 8: Interactive effects of harvesting times x accessions on the degree of sphericity of seed of roselle

	Harvesting times			
Accessions	Physiological maturity	One week after physiological maturity	Two weeks after physiological maturity	Means
HS08	0.76	0.75	0.75	0.75
HS11	0.75	0.74	0.74	0.74
HS19	0.74	0.73	0.73	0.73
HS25	0.76	0.75	0.75	0.75
HS27	0.75	0.74	0.74	0.74
HS32	0.74	0.73	0.73	0.73
HS41	0.74	0.73	0.73	0.73
HS58	0.75	0.74	0.74	0.74
HS59	0.74	0.73	0.73	0.73
HS69	0.74	0.73	0.73	0.73
HS83	0.74	0.73	0.73	0.73
HS86	0.76	0.75	0.75	0.75
Means	0.74	0.73	0.73	
HSD (0.05): accessions = 0.102; harvesting times = 0.010; accessions x harvesting times = 0.010				

at the physiological maturity stage had the highest angle of repose (20.57°), significantly different from all the other treatment combinations. Among the roselle accessions, the highest angle of repose (20.13°) was produced by seeds of accessions HS08 and the least angle of repose (19.77°) was by HS11, HS27, and HS58 (Table 6). Among the harvesting times, seeds harvested at the physiological maturity stage had the highest angle of repose (20.07°), significantly different from those harvested at one and two weeks after physiological maturity (19.84°), which had the lowest (Table 6).

4.7. Effects of Harvesting Times and Accessions on the 1000 Seed Mass of Roselle. There were significant harvesting times x roselle accessions interactions ($p < 0.01$) for the 1000 seed mass (Table 7). Seeds of accessions HS41 and HS69 harvested. The three harvesting times had the heaviest mass (0.05 g), significantly different from all the other treatment combinations. Among the roselle accessions, the heaviest mass (0.05 g) was produced by seeds of accessions HS41 and HS 69, and the lightest (0.03 g) was by HS11, HS19, HS27, HS32, HS58, HS59, and HS83 (Table 7). Among the harvesting times, there were no significant differences between the mass of the seeds harvested and the three harvesting times (Table 7).

4.8. Effects of Harvesting Times and Accessions on the Degree of Sphericity of Seed of Roselle. There were significant harvesting times x roselle accessions interactions ($p < 0.01$) for the seed degree of sphericity (Table 8). Seeds of accessions HS08, HS25, and HS83 harvested at the physiological maturity stage had the highest degree of sphericity (0.76), significantly different from all the other treatment combinations. Among the roselle accessions, the highest seed degree of sphericity (0.75) was produced by seeds of accessions HS08, HS25 and HS 86, and the lowest seed degree of sphericity was by HS19, HS32, HS41, HS59, HS69, and HS83 (Table 8). Among the harvesting times, seeds harvested at the physiological maturity stage had the highest seed degree of sphericity (0.74), significantly different from those harvested at one and two weeks after physiological maturity, which had the lowest (0.73) (Table 8).

4.9. Effects of Harvesting Times and Accessions on the Surface Area of Seed of Roselle. There were significant harvesting times x roselle accessions interactions ($p < 0.01$) for seed surface area (Table 9). Seeds of accession HS08 harvested at the physiological maturity stage had the highest surface area (18.57 mm^2), significantly different from all the other treatment combinations. The smallest surface area (17.83 mm^2) was produced by seeds of accessions HS27, HS32, HS69, HS11, HS19, HS41, HS59, HS53, and HS83, which were harvested at both one and two weeks after physiological maturity. Among the accessions, the highest seed surface area (18.21 mm^2) was produced by HS08, HS25, and HS86 and the least surface area (17.90 mm^2) was produced by accessions HS27, HS32, HS69, HS11, HS19, HS41, HS59, HS53, and HS83. Between the harvesting times, roselle seeds harvested at the physiological matured stage produced the significantly highest surface area (18.11 mm^2) and the least (17.88 mm^2) was produced by those harvested at both one and two weeks after the physiological maturity stage.

4.10. Correlations among the Physical Properties of Seeds of Roselle. There were positive and highly significant correlations among seed width and the following geometric parameters: seed angle of repose ($r = 0.93$), seed length ($r = 0.84$), seed mean diameter ($r = 0.89$), seed degree of sphericity ($r = 0.68$), and seed surface area ($r = 0.94$). There were also positive and significant correlations among seed thickness and following geometric parameters: seed mass ($r = 0.59$), seed degree of sphericity ($r = 0.79$), and seed surface area ($r = 0.63$). Furthermore, there were positive and highly significant correlations among seed degree of sphericity and length ($r = 0.82$), with seed mean diameter ($r = 0.73$).

Table 9: Surface area (mm2) of roselle seeds accessions as influenced by harvesting times and accessions.

	Harvesting times			
Accessions	Physiological maturity	One week after physiological maturity	Two weeks after physiological maturity	Means
HS08	18.57	18.03	18.03	18.21
HS27	18.03	17.83	17.83	17.90
HS25	18.23	18.03	18.03	18.21
HS86	18.23	18.03	18.03	18.21
HS32	18.03	17.83	17.83	17.90
HS69	18.03	17.83	17.83	17.90
HS11	18.03	17.83	17.83	17.90
HS19	18.03	17.83	17.83	17.90
HS41	18.03	17.83	17.83	17.90
HS59	18.03	17.83	17.83	17.90
HS58	18.03	17.83	17.83	17.90
HS83	18.03	17.83	17.83	17.90
Means	18.11	17.88	17.88	
HSD (0.05): accessions = 0.120; harvesting times = 0.111; accessions x harvesting times = 0.300				

5. Discussion

The seed moisture content of most crops is generally high at physiological maturity when the seeds have attained maximum seed filling and dry weight [20]. In this study, seeds of all accessions harvested at the physiological maturity stage recorded the highest moisture contents, implying that the environment influenced the level of moisture content of the seed and not its genetic makeup. Araujo et al. [12] opined that harvesting a crop at different times affected the physical properties of its seeds since the moisture content of the seed was positively related to its physical properties [21, 22]. Consequently, it is not surprising that seeds of all accessions with the highest moisture content also recorded the best seed physical properties. Sánchez-Medoza et al. [13] also reported that the physical properties of roselle seeds were positively affected by the seed's moisture content and the locality of harvest (environment) when they conducted experiments in three different countries.

There were increases in the three principal dimensions (length, width, and thickness) of seed for accession HS08 harvested at the physiological maturity stage compared to the other treatment combinations. This could be attributed to the genetic differences between the accessions, as Niveditha et al. [23] reported that variation in seed physical properties in some crops was due to the genotypic differences between the varieties of the crop. Accession HS08 harvested at the physiological maturity stage also recorded increases in the geometric mean diameter, sphericity, and surface area. These observed increases could be due to their dependence on the three principal dimensions of the seed. The surface area of seeds plays an important role in determining the projected area of the seeds moving in the turbulent air stream and is thus useful in designing the seed cleaners, separators, and conveyors. Increased surface area to volume ratio also elevates heat and mass transfer rate of seeds facilitating drying and cooling operations [14]. The degree of sphericity indicated that the seeds were spherical in shape and could slide on flat surfaces easily. This was within the range obtained by Sánchez-Medoza et al. [13] for roselle seeds from three different countries but higher than the values obtained by Omobuwajo et al. [24]. This property helps in the design of hoppers and dehulling equipment for the seed.

Seeds of accession HS08 harvested at the physiological maturity stage also had the highest angle of repose different from all the other treatment combinations. The angle of repose measures the cohesion among the individual units of seeds and their kernels. Generally, smaller seeds show higher cohesion with a lower angle of repose than larger ones [14]. The higher seed moisture content of all the accessions at the physiological maturity stage could explain the greater angle of repose of the seeds since seeds stick together at higher moisture content, resulting in less flowability and better stability. The angle of repose is important in designing hopper openings, sidewall slopes of storage bins, and chutes for bulk transporting of seeds [25]. The present study established positive correlations between the principal dimensions and the other seed properties, which also corroborates the findings of Bamgboye and Adejumo [14].

6. Conclusion

This study has clearly demonstrated that roselle seeds should be harvested at the physiological maturity stage to ensure good physical properties for mechanized postharvest operations for successful long-term storage. Accession HS08 harvested at the physiological maturity stage produced the best physical properties in terms of the length, width, thickness, geometric mean diameter, angle of repose, degree of sphericity, surface area, and seed mass. These properties would be key in the planning and design of mechanized equipment for seed production, harvesting, cleaning, processing, and storage handling of roselle seeds.

Data Availability

The data supporting the findings of the study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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