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Physical and mechanical properties of Arabica coffee (*Coffea arabica* L.) cherries and beans in Rwanda

[1,2,*]Bizimungu, G., [1]Ahouansou, R.H. and [1]Semassou, G.C.

[1]*Université d'Abomey-Calavi, Ecole Polytechnique d' Abomey-Clavi, 01 BP 2009 EPAC, Benin*
[2]*Rwanda Polytechnic, Integrated Polytechnic Regional College of Karongi, P.O Box 85 Karongi, Rwanda*

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Abstract

Arabica coffee is worldwide predominated and accounts for about 97% of Rwandan coffee production. Up to 70% of exported washed coffee is pulped using high-capacity coffee pulping machines while the remaining is pulped by smallholder farmers. However, the lack of information on coffee beans can affect depulping activity, especially when using locally-made pulping machines. Therefore, this study aimed to investigate Arabica coffee's physical and mechanical properties from eight districts of Rwanda to improve the pulping process. The coffee parameters were investigated using precision measuring instruments and statistically analysed using One-Way ANOVA, one-sample t-test, and the Turkey multi-comparison method in GraphPad Prism 9.3.1 software. The investigation found the mean length of 15.40 mm, 12.12 mm and 11.85 mm, the width of 13.03 mm, 8.26 mm and 8.15 mm, the thickness of 13.03 mm, 4.88 mm and 4.87 mm for Arabica cherries, wet parchment beans and dried parchment beans, respectively. Their corresponding average mass of 1.53 g, 0.43 g, and 0.173 g, the density of 1.006 g/mL, 0.894 g/mL and 0.390 g/mL for Arabica cherries, wet parchment beans, and dried parchment beans, respectively. The Arabica showed a true volume of 1.531 mL and 0.271 mL for cherries and dried coffee beans, respectively. The wet parchment coffee was dried from 29.9 to 10.8% wb. The dried parchment beans showed a coefficient of static-friction and fracture force of 0.585 and 29.85±6.81 kgf, respectively. The other parameters evaluated for cherries and dried parchment coffee beans include moisture content, true volume, density, porosity, sphericity, and angle of repose. The results showed that coffee's size, mass, densities, and diameters from different districts are significantly different at P-value < 0.05 and also showed a perfect correlation. Each of the above coffee parameters provides the general information needed to develop a pulping machine for cherries. Therefore, the small-scale coffee pulping machine should be developed, and properly adjusting the pulping unit to enhance the performance of the machine based mainly on the size, fracture force, and density of the coffee.

1. Introduction

Coffea arabica, Coffea canephora (C. Robusta), and *Coffea liberica* (Liberica coffee) are the predominated coffee species that originated in the Eastern, Central and Western regions of Africa, respectively. A highland *C. arabica* that is also predominated in Rwanda accounts for about 97% of the country's production (Promar Consulting, 2011) due to its high-yielding, excellent aroma, and flavour (Hakorimana and Akçaöz, 2017). This production contributes around 23% of the country's income. The Rwandan geographical conditions and growth factors contribute 40% and post-harvesting factors contribute 60% to the quality parameters of cherries and beans as well as cup quality (Hameed *et al.*, 2018). Based on the best weather conditions for *C. arabica*, the government of Rwanda is increasing the plantations of coffee trees across the country to top up at least 50% of the country's production.

According to Haile and Hee (2020), the coffee cherry's growth undergoes three stages before its harvesting, starting when it is green, to yellow, and then red (bright red, ripe red). The red ripens cherries harvesting either by stripping or selection method (Haile and Hee, 2020) contribute to the quality of coffee beans, especially in size, density, and fracture (Olika *et al.*, 2019). Additionally, the handpicking of the ripened cherries requires intensive workers and is laborious, and

*Corresponding author.
Email: *bizimungugaspard@gmail.com*

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it is preferable in hilly countries like Rwanda. The handpicking of cherries enhances the pulping performance, resulting in high-quality coffee beans (Ismail and Shamsudin, 2013). The coffee cherries generally have oval fruits that mostly contain two seeds inside the pulp called coffee beans (Ghosh *et al.*, 2014), however, one to seven cherries probably contain one big seed called ''pearberry''. Therefore, there are four main types of bean shapes: standard, peaberry, triage and elephant (Ghosh *et al.*, 2014; Olika *et al.*, 2019). The last three types of beans also have an impact on the coffee quality due to their abnormal shapes. Then, during the pulping process, the machine needs to squeeze the cherry into a small clearance to separate pulp and beans. Therefore, using a small-scale depulper without selecting the good cherries affects coffee quality leading to the losses of the local farmers.

Moreover, in 2018/2019, the 142,350 MT (Million Tons) of coffee cherries harvested in Rwanda by handpicking (Promar Consulting, 2011; Hakorimana and Akçaöz, 2017; Centre for the Promotion of Imports from Developing Countries (CBI), 2018) provided 15,000 to 22,000 MT parchment coffee beans exported annually. In these parchments, up to 70% pulped from up to 307 Coffee Washing Stations (CWSs) that are distributed in the country (CBI, 2018).

The parchment coffee produced from CWSs revealed a higher quality than the parchment coffee beans produced by smallholders locally using traditional pulping techniques that covers less than the remaining 30% of the coffee pulped in CWSs. These traditional pulping methods are rarely performed using hands and mortar and pestle, and most of the farmers are still using locally fabricated drum pulpers. These uncontrolled pulping methods which are not based on coffee information affect the repetition of coffee quality at the market level.

Therefore, in this study, the investigation of the physical and mechanical parameters of coffee cherries and beans that define the coffee quality in each particular region of Rwanda has been performed. The effect of each coffee attribute on the pulping process was analysed to improve the de-pulping process. The coffee samples from the main eight coffee-producing districts were used to gather coffee quality information across the country.

2. Materials and methods

2.1 Description of the sites

Rwanda is geographically located in Eastern Africa at 1000-2000 m altitude and an average temperature of 20°C (Usangabandi, 2021). Arabica coffee cherries used in this study were harvested in October 2021 from eight districts: Gakenke, Gicumbi, Nyabihu, Kayonza, Kamonyi, Huye, Nyamasheke, and Rutsiro across the four provinces of Rwanda.

2.2 Experimental design

The fresh cherries were harvested using handpicking by the selected men and women coffee farmers who are involved in pulping processing at each Coffee Washing Station (CWS). Then, 15 kg (basic samples) of cherries were collected at SCIMPACT Ltd (SCI-MI) to conduct experimental tests. From the basic samples, 8 samples of 20-cherries each were formed and tagged with the district name of the cherries' origin. During the hand-pulping process, peaberry or three beans inside of some cherries were not used in the properties' investigation. However, during pulping, the cherries with three seeds were also found at the same ratio of 1 seed-cherries as presented in Figure 1. After, hand-depulping the sampled cherries, 8 sub-samples of twenty parchment beans were also formed. The abnormal beans were rejected.

Figure 1. Half-hand pulped coffee cherries with three beans

The electrical oven (binder) used was set at 105.5°C inside the drying chamber and 22.6°C at room temperature, as has been used in different studies to measure the moisture of parchment coffee (Ismail *et al.*, 2014; Jackson *et al.*, 2016). Therefore, some of the other instruments used in the tests of this study are a digital balance and moisture content meter as shown in Figure 2.

Figure 2. Instruments used for conducting physical properties of coffee cherries and beans (a) Electronic digital balance-SCI-MI-04, (b) Coffee Pro, Moisture-MAC and (c) Electrical oven-binder

2.3 Physical properties

The physical properties of coffee beans investigated were mass using a digital balance with a sensitivity of 0.0001 mm, moisture content using a Coffee Moisture meter with 0.01% wb (wet basis) sensitivity and drying using an oven as shown in Figures 2a, 2b and 2c, respectively. The size was measured using a digital

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vernier calliper (RAIDER® Japan RM500) with 0.01 mm, the ten cherries bulk and apparent volumes using graduated cylinders of 250 mL and ten parchment coffee beans using 50 mL. The mass, size and volume of fresh cherries and wet parchments were measured on the same day within 24 hrs. Therefore, the dimensions of coffee cherries and parchments were measured for each of the 8 formed samples using the digital vernier calliper according to Worku *et al.* (2019); their mass and density were also measured using the digital balance according to Ahouansou *et al.* (2010) and the moisture content and porosity were measured as suggested by Worku *et al.* (2019). The mass of twenty cherries and twenty parchments were measured with triplications while the mass of 1 bean was individually measured for the twenty beans. Next, the cherries were hand depulped to obtain parchments and mucilage was removed by cleaning beans. The wet-parchment coffee beans were dried using an oven from initial moisture content as conducted by Ismail *et al.* (2014). The moisture content of the wet parchment coffee beans was measured 7 times each for 30 min during the drying process by using a coffee Moisture content Meter. The initial water content found in the parchment was 29.9% wb and after drying the final water content was 10.8% wb.

The dried parchment coffee beans at 10.8% wb were filled up to the top of the graduated container of 500 mL to measure the bulk volume. The mass of the beans for the corresponding bulk volume was measured with three trials using the electronic balance. The corresponding bulk density of 1 parchment coffee bean was determined as the ratio of the mass of the parchments filled the cylinder to its volume according to Worku *et al.* (2019). The apparent volume of 100 beans was measured using a graduated cylinder of 150 mL. The apparent/true-volume difference in water displacement was recorded for triplications. The readings were recorded 5 mins after dropping all beans in water. The true density was determined using the volumes and mass measured according to *Saparita et al.* (2019). To conduct the properties of dried beans, the 8 samples of 20 beans each were dried separately. The other physical parameters, such as arithmetic mean diameter, equivalent mean diameter, geometric diameter, volume, porosity, aspect ratio, and cross-section area were calculated using the following Equations (1-7) (Bagan *et al.*, 2015). The selection of cherries was performed based on colour observation (Yuwana *et al.*, 2015).

$$Arithmetic\ Mean\ Diameter\ (ADM) = (L + W + T)/3 (mm) \quad (1)$$

$$Equivalent\ Diameter\ (D_E) = 1.24V^{1/3} \quad (2)$$

$$Geometric\ Diameter (D_G) = \sqrt[3]{L * W * T} (mm) \quad (3)$$

$$Volume\ (V) = \frac{\pi}{6} * L * W * T (mm^3) \quad (4)$$

$$Aspect\ Ratio\ (R_a) = W/L \quad (5)$$

$$Cross\ Section\ Area\ (CSA) = \frac{\pi}{4} \frac{(L+W+T)^2}{3} (mm^2) \quad (6)$$

$$Porosity\ (P) = (1 - \rho_b/\rho_t) \quad (7)$$

where, *L*: length, *W*: width, *T*: thickness, *V*: volume : ρ_b bulk density and ρ_t: true density

2.2 Mechanical properties

The mechanical properties of beans were expressed by Palilo *et al.* (2018). The following mechanical characteristics of beans and cherries were determined. The coefficient of static friction, and filling angle of repose were measured with three replications and analyzed using a one-sample t-test. The angle of repose and coefficient of parchment coffee beans were recorded when the first beans started sliding on the aluminium sheet that was raised manually using a system of screws and nuts (Kuala *et al.*, 2019). The fracture force of the 50 Arabica coffee beans was measured using numerical a system of balance and screw-nut as shown in Figure 3. The filling angle was performed using a PVC cylinder of 110 mm diameter and 150 mm height together with a graduated surface (Ismail *et al.*, 2014). The emptying angle of repose was measured by filling the dried parchment coffee beans in a hallowed Plywood box of 20cm×20cm with sliding at the opening at one side. To allow the filled beans to the top to flow once the gate is removed quickly upward via the sliding slots. The parchment coffee beans used were dried at 10.8% wb having around 5 kg.

Figure 3. Measuring fracture force using a numerical balance and a system of screw and nut

The mechanical properties were determined according to Ismail and Shamsudin (2013), coefficient of static friction (Yuwana *et al.*, 2015), coefficient of contact (Worku *et al.*, 2019), shape index (Saparita *et al.*, 2019), sphericity (Diaferia, 2019), average hardness (Saparita *et al.*, 2019), and fracturability (Kuala *et al.*, 2019) using Equation 8 to 12.

$$Angle\ of\ repose\ (\theta) = tan^{-1}(2H/D) \quad (8)$$

$$Coefficient\ of\ friction\ (\mu) = tan\,\theta \quad (9)$$

$$Shape\ Index\ (SI) = L/\sqrt{(W * T)} \quad (10)$$

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$$Sphericity\ (S_P) = \frac{(l \times w \times t)^{\frac{1}{3}}}{l}\ (mm) \quad (11)$$

$$Roundness\ ratio\ (R_r) = r/R \quad (12)$$

Where D: diameter of the cone cylinder, H: Height of the head, N: number of measurements, R: larger radius, and r: small radius.

2.4 Statistical analysis

GraphPad Prism 9.3.1 statistical software was used to analyse the parameters of Arabica coffee (Bizimungu *et al.*, 2022; Figueroa *et al.*, 2022). One-way ANOVA was selected to evaluate the overall significant difference and compare the mean of every coffee property at the district level (Huzsvai *et al.*, 2022). The analysis was performed at significant level limits of 95% and a confidence level of 5%. Turkey was used to find out the mean values, standard variations and significant difference level, correlation co-efficiency for the measured and calculated parameters. A statistical analysis was also conducted to evaluate variations in the physical properties of coffee cherries and beans from different regions. The one-sample t-test and Wilcoxon test were used to find the mean and Standard Deviation (SDT) for data recorded with triplications such as mass, true/apparent volume and a bulk volume of 100 beans, coefficient of friction, filling and emptying angle of repose. Hence, the cherries' conditions were the key to the above analyses.

3. Results

3.1 Parameters of coffee cherries

The cherries overcame different stages to mature, and the cherries used in the tests were randomly selected from the main samples collected by farmers. Therefore, before starting experiments, the colour of the fresh cherries was investigated and it was found that 71.25% were ripened, 21.87% were semi-ripened and 6.87% were overripened of the 8 basic samples formed per district as shown in Table 1. The immersed and floaters cherries among the 8 basic samples were 68.13% and 31.87%, respectively.

3.1.1 Mass and volume of coffee cherries

The average mass and volume distribution of Arabica coffee cherries from 8 districts of Rwanda were evaluated as shown in Figures 4 and 5, respectively. The maximum and the minimum mass of cherries investigated were 18.05g and 12.33 g from Gakenke and Kamonyi, respectively as shown in Figure 4. Their corresponding maximum and minimum true volume investigated were 17.0 mL and 11.5 mL from Gicumbi and Kamonyi, respectively as shown in Figure 5.

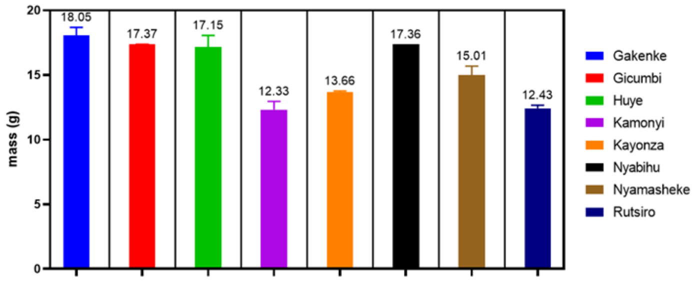

Figure 4. Mean mass of Arabica coffee cherries from 8 Rwandan districts.

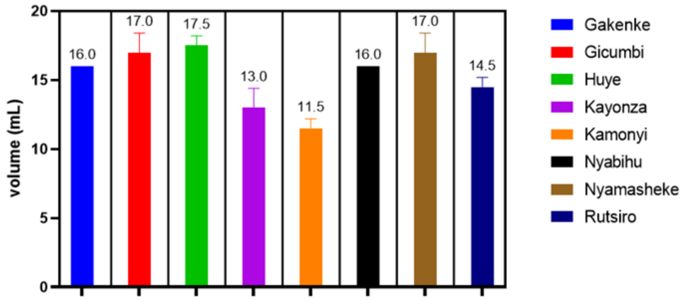

Figure 5. Mean mass of Arabica coffee cherries from 8 Rwandan districts.

3.1.2 Mean dimensions of coffee cherries

The sizes of 10 cherries were measured individually for the 8 samples. The average length, width and thickness of coffee cherries from the 8 districts of Rwanda are shown in Figure 6. The size of cherries at a district level showed a higher and smaller length of 16.30 mm and 14.47 mm from Gakenke and Kamonyi districts, respectively, with width and thickness of 14.08 mm and

Table 1. Characteristics of 20 cherries used in the investigation of coffee quality parameters.

S/N	District	Semi-ripe	Ripened	Overripened	Immersed	Floaters
1	Gakenke	5	15	0	16	4
2	Gicumbi	9	11	0	16	4
3	Huye	2	18	0	13	7
4	Kamonyi	6	8	6	8	12
5	Kayonza	4	15	1	15	5
6	Nyabihu	2	18	0	20	0
7	Nyamasheke	2	18	0	15	5
8	Rutsiro	5	11	4	6	14
Total		35	114	11	109	51
Percentage (%)		21.87	71.25	6.87	68.13	31.87

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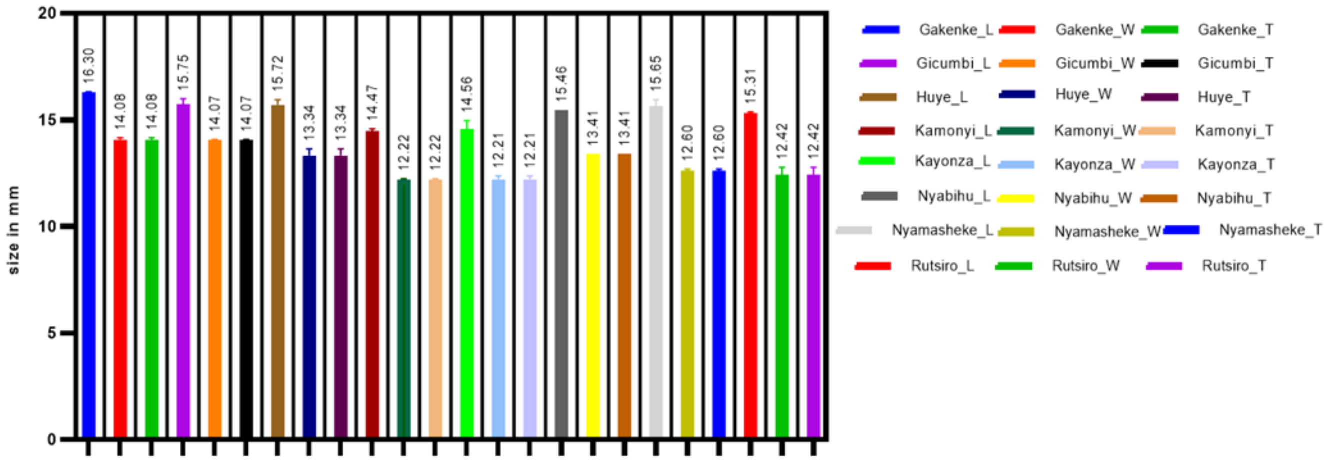

Figure 6. Average dimensions of coffee cherries harvested in 8 districts of Rwanda.

12.21 mm from Gakenke and Kayonza districts, respectively as shown in Figure 6. The thickness was identical to the width as the cherries have an ellipsoidal shape.

The average dimensions (length, width and thickness) of cherries were used to determine the mean sphericity, Arithmetic Mean Diameter (ADM), Geometric Diameter (GD) Equivalent Diameter, Aspect ratio (Ra), Shape index (SI) and Cross-Section Area (CSS) using Equations (1-12). It was observed that most maximum and minimum of the determined parameters are from Gakenke and Kayonza districts, respectively as shown in Table 2. Therefore, the Rwandan Arabica coffee cherries showed a mean length of 15.40±0.62 mm, a width of 13.0±0.75 mm and a thickness of 13.03±0.75 mm as shown in Table 3. The mean parameters of coffee cherries were 0.89±0.01, 13.69±0.74 mm, 13.77±0.72 mm, 13.77±0.72 mm, 0.84±0.02, 1.18±0.04 and 15.22±2.91 mm^2 for sphericity, Arithmetic Mean Diameter (ADM), Geometric Diameter (GD) Equivalent Diameter, Aspect ratio (Ra), Shape index (SI), and Cross-Section Area (CSS) as indicated in Table 3. The results showed the corresponding mean mass and volume of 15.42 g and 15.31 mL of 10 Arabica coffee cherries as represented in Table 3.

Table 2. Determined average dimensions of coffee cherries harvested in 8 districts of Rwanda

S/N	District	Sphericity	AMD (mm)	GD (mm)	ED (mm)	Ra	SI	CSS
1	Gakenke	0.90±0.04	14.82±0.63	14.77±0.63	86.18±6.39	0.86±0.66	1.16±0.09	13.32±6.62
2	Gicumbi	0.92±0.03	14.62±0.94	14.60±0.94	85.25±9.31	0.89±0.05	1.12±0.63	10.51±5.07
3	Huye	0.89±0.03	14.13±0.82	14.08±0.83	79.38±8.07	0.85±0.05	1.18±0.07	14.94±5.31
4	Kamonyi	0.89±0.05	12.90±1.09	12.84±1.10	68.05 ±10.24	0.84±0.07	1.19±0.11	15.90±7.31
5	Kayonza	0.89±0.04	12.99±0.63	12.94±0.64	68.69±5.86	0.84±0.06	1.19±0.08	15.86±6.06
6	Nyabihu	0.90±0.02	14.09±0.83	14.06±0.83	79.50±8.44	0.86±0.04	1.15±0.05	13.23±4.14
7	Nyamasheke	0.86±0.04	13.61±1.18	13.53±1.19	73.58 ±11.45	0.80±0.05	1.24±0.09	19.44±5.95
8	Rutsiro	0.87±0.05	13.38±1.22	13.30±1.22	71.67 ±11.52	0.81±0.07	1.23±0.12	18.55±7.31

Table 3. Mean parameters of coffee cherries from Rwanda

Mean parameters of cherries	Value	SDT	*SEM*
10-cherries mass (g)	15.42****	± 2.33	0.58
10-cherries true volume (mL)	15.31****	± 2.21	0.54
1-Bean True density (g/mL)	1.006	-	-
Length (mm)	15.40****	± 0.62	0.62
Width (mm)	13.03****	± 0.78	0.79
Thickness (mm)	13.03****	± 0.78	0.79
Sphericity	0.89	± 0.01	0
Arithmetic Mean Diameter (mm)	13.69****	± 0.74	0.26
Geometric Diameter (mm)	13.77****	± 0.72	0.25
Equivalent Diameter (mm)	13.77****	± 0.72	0.25
Aspect ratio	0.84****	± 0.02	0.01
Shape Index	1.18****	± 0.04	0.01
Cross-Section Area (mm^2)	15.22****	± 2.91	1.03

****: Significant difference at P-value < 0.0001

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3.2 Parameters of parchment coffee beans

3.2.1 Moisture content

The initial moisture found in wet parchment coffee beans was 29.9% wb and the final moisture found in the dried parchment coffee beans was 10.8% wb. These moisture contents were obtained during the drying process of the parchment coffee beans, measured every 30 mins.

3.2.2 Mean dimensions of Arabica parchment coffee beans

The parchment beans were dried from 29.9% wb and 10.8% wb. The tests (see Tables 4 and 5) showed that the parchments decreased in size as their moisture content decreased. The mean at the district and country-level, respectively were determined together with standard deviations and Standard Error Mean (SEM) of the principal dimensions of parchments. The higher and smaller length, width and thickness of wet parchment beans were 13.28 mm and 11.50 mm from Gakenke and Kamonyi, 8.51 mm and 8.00 mm from Gakenke and Nyamasheke, and 5.16 mm and 4.72 mm from Nyabihu and Nyamasheke, respectively as shown in Figure 7.

Their dried parchments coffee beans had higher and smaller length, width and thickness of 12.71 mm and 11.20 mm from Gakenke and Kayonza, 8.4 mm and 7.76 mm from Gicumbi and Kamonyi, and 5.08 mm and 4.67 mm from Gicumbi and Kamonyi, respectively as shown in Figure 8.

The mean length, width and thickness were determined at a confidence level of 95% for the wet and dried. The mean dimensions of dried coffee beans showed a higher correlation of 0.76 and 0.28 between length, width and thickness, respectively at a confidence level of 95%. The correlation found between width and thickness was 0.37. Therefore, the mean length of 12.23±0.51 mm and 11.81±0.40 mm, the width of

Table 4. Determined average dimensions of coffee beans from 8 districts of Rwanda at 29.9% wb.

S/N	District	Sphericity	AMD (mm)	GD (mm)	ED (mm)	Ra	SI	CSS
1	Gakenke	0.62±0.02	8.98±0.41	8.34±0.33	29.42±6.39	0.64±0.03	2.00±0.13	61.11±3.14
2	Gicumbi	0.66±0.03	8.42±0.94	7.91±0.24	27.48±1.25	0.71±0.05	1.84±0.12	58.20±2.86
3	Huye	0.63±0.02	8.41±0.48	7.82±0.43	26.60±2.38	0.66±0.05	1.96±0.14	60.91±2.84
4	Kamonyi	0.66±0.02	8.12±0.56	7.61±0.53	25.79 ±2.91	0.71±0.06	1.85±0.11	58.65±3.11
5	Kayonza	0.65±0.02	8.49±0.38	7.96±0.64	27.60±2.06	0.69±0.04	1.88±0.09	59.04±2.67
6	Nyabihu	0.65±0.02	8.64±0.29	8.11±0.28	28.48±1.82	0.67±0.02	1.89±0.09	58.35±2.80
7	Nyamasheke	0.63±0.03	8.31±0.48	7.71±0.42	25.90±2.19	0.66±0.07	1.98±0.18	61.17±3.14
8	Rutsiro	0.64±0.04	8.30±0.56	7.71±0.49	26.07±2.74	0.68±0.08	1.95±0.20	60.43±5.58

Table 5. Determined average dimensions of coffee beans from 8 districts of Rwanda at 10.8% wb

S/N	District	Sphericity	AMD (mm)	GD (mm)	ED (mm)	Ra	SI	CSS
1	Gakenke	0.63±0.04	8.68±0.54	8.08±0.53	28.12±3.24	0.65±0.07	1.97±0.19	59.85±4.38
2	Gicumbi	0.67± 0.03	8.33±0.24	7.85±0.20	27.22±1.12	0.72±0.06	1.80±0.12	57.43±2.95
3	Huye	0.64±0.02	8.20±0.39	7.65±0.33	25.75±1.67	0.68±0.05	1.91±0.10	60.22±1.80
4	Kamonyi	0.65±0.05	7.89±0.75	7.73±0.84	24.44±4.45	0.69±0.13	1.91±0.34	58.19±4.49
5	Kayonza	0.67±0.02	8.04±0.31	7.56±0.30	25.64±1.67	0.73±0.04	1.79±0.09	57.54±2.83
6	Nyabihu	0.65±0.03	8.30±0.51	7.76±0.42	26.44±1.99	0.69±0.07	1.89±0.16	59.40±2.89
7	Nyamasheke	0.64±0.03	8.33±0.45	7.80±0.47	26.62±2.90	0.65±0.09	1.93±0.18	58.45±2.62
8	Rutsiro	0.65±0.03	8.29±0.52	7.75±0.45	26.43±2.48	0.69±0.06	1.89±0.16	58.85±5.31

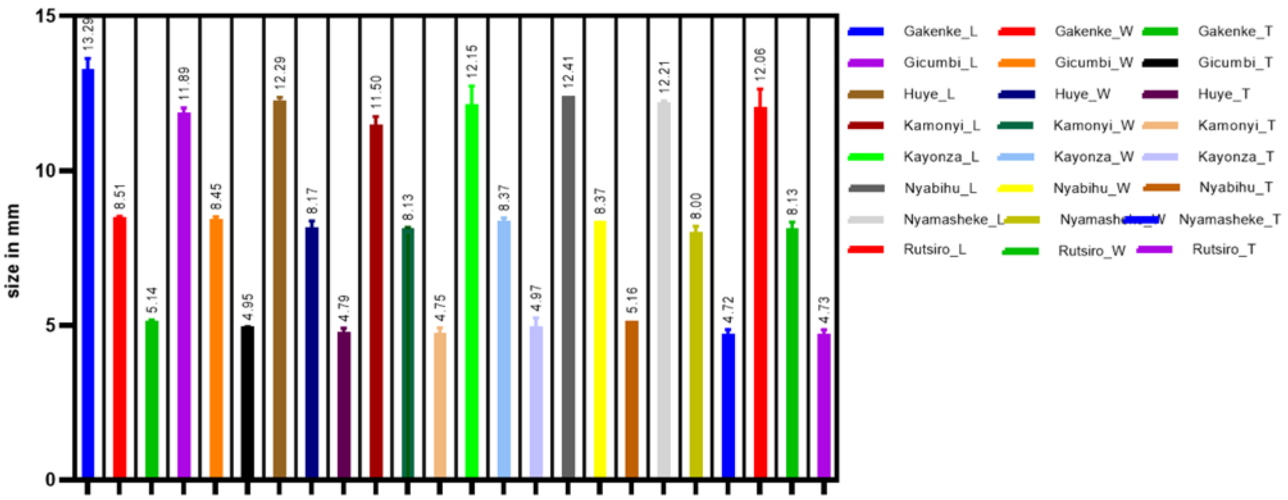

Figure 7. Average dimensions of Arabica parchment coffee beans at 29.9% wb.

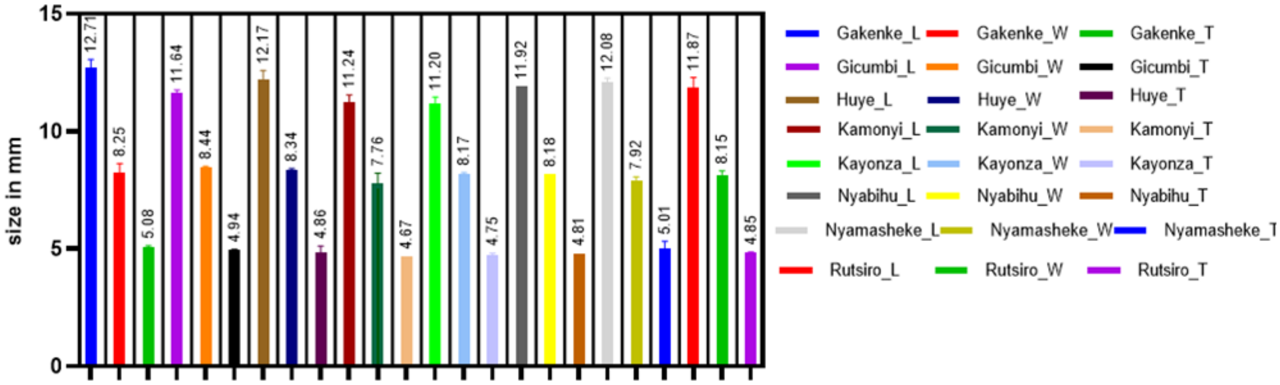

Figure 8. Average dimensions of Arabica parchment coffee beans at 10.8% wb.

8.26±0.17 mm and 8.12±0.20 mm and the thickness of 4.89± 0.22mm and 4.84±0.14 mm were for wet and dried parchment coffee at 29.9% wb, and 10.8% wb, respectively, as shown in Tables 6 and 7.

3.2.3 Mass of parchment coffee beans

The parchment was dried from 29.9% wb and 10.8% wb and the decrease in mass was measured. The average mass of 10 parchment coffee beans was investigated in every district. The maximum and minimum mass of 10-wet parchment coffee beans were 5.49 g and 3.35 g from Gakenke and Kamonyi districts, respectively as shown in Figure 9a. The maximum and minimum mass of 10-dried parchment coffee beans of 1.97 g and 1.03 g from Gicumbi and Rutsiro districts, respectively as shown in Figure 9b. The mean mass of 4.30 g and 1.49 g of the beans at initial moisture and final for wet and dried parchment coffee beans, respectively were determined at a confidence level of 95% as shown in Tables 6 and 7.

3.2.4 Volume of 100 beans and density of the dried parchment coffee beans

The bulk volume and true volume of 100 beans of Arabica coffee from 8 districts of Rwanda were 17.35±0.79 mL and 27.33± 1.15mL, respectively. The corresponding determined bulk density and apparent density were 0.390 g/mL and 0.637 g/mL, respectively as shown in Table 7.

3.3 Mechanical properties

3.3.1 Filling angle, emptying angle and coefficient of friction of parchment coffee beans

The mean value angle calculated from the 3 replications measurements was 38.68±0.39^o and 23.3±0.24^o for the filling angle and the emptying angle

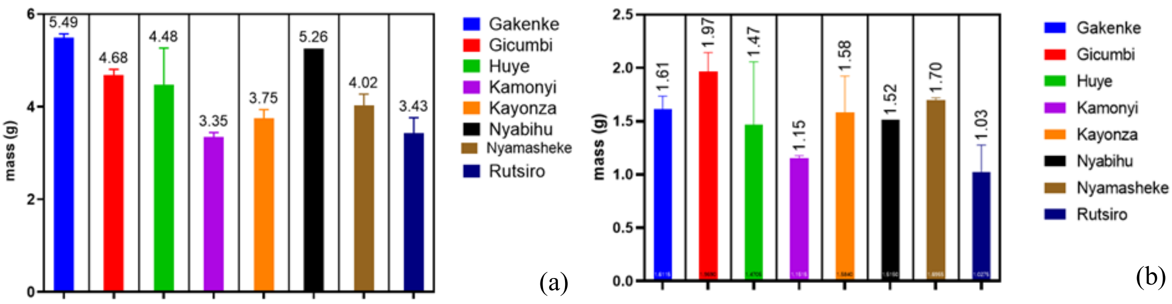

Figure 9. Mass of Arabica parchment coffee beans at 29.9% wb and 10.8% wb.

Table 6. Mean parameters of wet parchment coffee beans at 29.9% wb

Mean parameters	Value	SDT	*SEM*
Moisture content (wb)	29.9%	-	-
10-bean mass (g)	4.30****	± 0.80	0.28
Deter. volume bean (mm^3)	258.80****	± 22.98	8
Length (mm)	12.23****	± 0.51	0.18
Width (mm)	8.26****	± 0.17	0.06
Thickness (mm)	4.89****	± 0.18	0.06
Sphericity	0.65****	± 0.01	0.00
AMD (mm)	8.25****	± 0.23	0.08
GD (mm)	7.72****	± 0.21	0.07
ED (mm)	8.05****	± 0.23	0.08
Aspect Ratio	0.68****	± 0.02	0.01
Shape Index	1.88****	± 0.06	0.02
Cross-Section Area (mm^2)	58.74****	± 1.02	0.36

****: Significant difference at P-value $<$ 0.0001

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Table 7. Mean parameters of dried parchment coffee beans at 10.8% wb.

Mean parameters of cherries	Value	SDT	*SEM*
Moisture content (wb)	10.8%	-	-
100 Bean mass (g)	17.41****	0.76	0.25
Mass of 10 parchment beans (g)	1.49****	0.29	0.10
Mass of beans in 500 mL (g)	195.30****	± 0.02	0.01
100 beans-true volume (mL)	27.33***	± 1.15	0.66
100 beans bulk volume (mL)	17.35***	± 0.79	0.99
Apparent density (g/mL)	0.637	-	-
Bulk density (g/mL)	0.390	-	-
Porosity	0.38		
Length (mm)	11.81****	± 0.48	0.17
Width (mm)	8.12****	± 0.20	0.07
Thickness (mm)	4.84***	± 0.14	0.05
Sphericity	0.65****	± 0.01	0.00
Coefficient of Static Friction	0.58**	± 0.03	0.02
Fracture force (kgf)	29.84****	± 6.81	0.96
Filling Angle of repose (^{o})	23.3****	± 0.24	0.13
Emptying Angle of repose (^{o})	38.68****	± 0.39	0.22
Arithmetic Mean Diameter (mm)	8.25****	± 0.23	0.08
Geometric Diameter (mm)	7.72****	± 0.21	0.07
Equivalent Diameter (mm)	7.91****	± 0.20	0.07
Aspect Ratio	0.68****	± 0.02	0.01
Shape Index	1.88****	± 0.06	0.02
Cross-section (mm^2)	58.74****	± 1.02	0.36

,*,**** : Significant difference at P-value < 0.01, < 0.001, and < 0.0001, respectively

respectively, as shown in Table 7. The mean value of the coefficient of static friction found was 0.58±0.03^o and the corresponding angle determined was 30.33±1.52^o as shown in Table 7.

3.3.2 Fracture force of the dried coffee beans

The fracture force was determined from the 50 beans measurements taken. The results showed the mean fracture force of 29.85±6.81 kgf needed to crush the beans mechanically as shown in Table 7.

3.3.3 Geometric mean, Equivalent and Arithmetic diameters, volume, cross-section area, sphericity, shape index and aspheric ratio, and porosity of parchment coffee beans.

The Geometric Diameter (GD), Equivalent Diameter (ED), Arithmetic Mean Diameter (AMD), Cross-Section Area (CSA), and Sphericity of parchment coffee beans at 29.9% wb and 10.8% wb, were determined using the mentioned empirical formulas from Equations (1-12) as shown in Tables 4 and 5, respectively (Hakorimana and Akçaöz, 2017). The porosity determined from the measured densities was 38.68%. It was observed that the maximum and minimum determined parameters in general were from Gakenke and Kamonyi, respectively. These mean parameters of wet parchment coffee beans at 29.9% wb were 7.72±0.21 mm, 8.05±0.23 mm, 8.25±0.23 mm and 58.74±1.02 mm^2 for Geometric Diameter (GD), Equivalent Diameter (ED), Arithmetic Mean Diameter (AMD) and Cross-Section Area (CSA) as indicated in Tables 6. Their corresponding mean parameters of dried parchment coffee beans at 10.8% wb were 7.72±0.21 mm, 7.91±0.20 mm, 8.25±0.23 mm and 58.74±1.02 mm^2 for Geometric Diameter (GD), Equivalent Diameter (ED), Arithmetic Mean Diameter (AMD) and Cross-Section Area (CSA) and were 0.65±0.01, 1.88±0.06 and 0.68±0.02 for Sphericity, shape index and Aspect Ratio as indicated in Tables 7.

3.4 Grading and pricing the Rwandan Arabica coffee beans

According to the Kenyan Arabica coffee beans grading system, the Arabica coffee beans ranging in size from 6.75 mm to 7.14 mm, and from 5.95 mm to 6.35 mm are classified in AA and AB grade, respectively (International Coffee Organization (ICO), 2018). Therefore, the Rwandan Arabica coffee beans can be ranked in AA grade with a mean length of 11.85 mm, a width of 8.15 mm and a thickness of 4.87 mm. The width of the Rwandan Arabica coffee showed an excellent size beyond the estimated size of grade AA. The pricing of the coffee beans also depends on the grade (Tesfa *et al.*, 2019), where AA is 5$/kg and AB is 4 $/kg. Bean weight is also positively correlated with AA bean size (Cheserek *et al.*, 2020), then the A grade cost of Arabica at the New York mark is 4.2 $/kg and the cost of Robusta is 2.29 $/kg in 2022 based on (Statista, 2023). Therefore, the Rwandan Arabica coffee beans price at the global market

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can range from 4.2$/kg to 5 $/kg of parchment coffee beans. Referring to how Rwanda is practising coffee grading locally, the coffee beans randomly selected across the country during the analysis can be graded A+ as all beans' sizes are greater than 7.5 mm. As, the grading is not only based on size but also on weight, therefore, the beans in the range of 7 mm showed 0.17 g/bean. According to the size and weight of Rwandan Arabica coffee beans, the beans' price can be around 5 $/kg in the New York market according to (Statista, 2023).

4. Discussion

The coffee quality is an important target in wet processing, therefore, after depulping cherries, the parchments start the drying process. Therefore, the Arabica coffee quality parameters were investigated to provide the necessary knowledge to improve the pulping process and quality of Rwandan coffee at the market level. The desired cherries ready to pulp are the red ripened cherries harvested immediately and not staying later than 24 hrs with two seeds inside that can be immersed in water during sorting. However, undeveloped well cherries can also sometimes be with one better seed, hence they are pulped separately from the good cherries. The investigation shows that there were 109 immersed and 57 floating cherries. However, the floater cherries are not for throwing away, they are pulped separately. Indeed, the floats may contain a parchment of good quality and an undeveloped parchment. Then, sorting of cherries should take place before pulping to improve the pulping machine's performance and after pulping to grade parchment coffee beans according to the standard. Thus, both properties of coffee cherries and parchment coffee beans need to be known by the coffee cultivator at harvesting and post-harvesting levels.

The mean mass of 10 cherries determined from the analysis was 15.42±2.33 g as shown in Table 3. The analysis showed that the mass of cherries evaluated from a single cherry individual of 1.53±0.23 g and 10 cherries of 15.42±2.33 g did not show a significant difference at P-value < 0.05 as shown in Table 3**.** The mean mass of 1.53±0.23 g of Rwandan Arabica cherry is greater than that of Robusta (1.35 g) and a fourth of Liberica cherry (5.31 g) from Malaysia, and less of Arabica (1.65 g) in India (Chandrasekar *et al.*, 1999; Ismail *et al*., 2014).

The mean mass of a wet parchment coffee bean and a dried parchment coffee bean found was 4.30±0.80 g, and 1.49±0.29 g, respectively as shown in Tables 6 and 7. It has been observed that the mass ratio of dried to coffee cherries and wet parchment coffee decreased by around 10 and 30%, respectively. The ratio of wet to dried coffee bean masses was revealed to be around 3 times (2.86). The average mass of dried Rwandan Arabica coffee (0.15 g) is like half of Liberica (0.26 g), less of the Robusta (0.20 g) evaluated in Malaysia, and higher of the Arabica (0.13 g) evaluated in Ethiopia (Ismail *et al.*, 2014; Melese *et a*l., 2020). Therefore, the mass of parchment is used to determine the pulping machine capacity, pulping efficiency, and pulping rate losses in wet and grading coffee about the size of beans at the market level.

The mean volume at the country level of the cherries was 15.31±2.21 mL as shown in Table 3, which is triple less than of Malaysian Liberica cherry (5.5 mL), higher than that of Robusta cherry volume (1.1 mL), and higher the Arabica (1.1 mL) evaluated in India (Chandrasekar *et al.*, 1999; Ismail *et al.*, 2014). The determined bulk volume for parchment coffee beans was 0.273 mL/bean.

The mass and volume do not have a direct effect on the performance of the depulping machine, however, volume help in designing the hopper (Ahouansou *et al.*, 2010) based on the capacity and feed rate of the machine and mass can help in accelerating the feeding of cherries into pulping unit due to the gravity. The mass and volume also helped in sorting the good cherries using the floating method by water to reduce the breakage of beans and increase the performance of the pulping machine during pulping operation. Thus, the correlation of volume and mass together in the coffee from one region can contribute to defining the quality of coffee at the consumer or market level. Thus, the analysis revealed that there is a great significant difference between the size, mass and volume, P-value < 0.05.

The corresponding true or apparent densities of cherries and wet beans measured were 1.006 g/mL and 0.637 g/mL. The results showed a bulk density determined was 0.390 g/mL for the Rwandan dried parchment coffee beans. Therefore, density is the key measure of grading coffee beans together with size to define a price. Installing a pulping machine in the area with a better density of parchment can bring enough income to smallholder coffee farmers. The densities in this study were a bit lower than the true density of coffee seeds (0.72 g/mL) and bulk density of coffee beans (0.590 g/mL) from the works conducted in Ethiopia (Olukunle and Akinnuli, 2012; Saparita *et al.*, 2019).

The porosity determined from the density was 38.68%. Initially, the mass that filled the container to determine the moisture content was 53.34 g, and this decreased to 37.94 g for the initial to the final moisture content of 29.9% wb to 10.8% wb, respectively. This implies that the water content from wet parchment coffee to the dried one is up to 28% of the initial moisture content. Therefore, the water content reduction in the parchment coffee beans obtained from the different samples during the drying process is in a range of 59.76 to 65.11% wb was calculated based on data shown in Figure 10. Then, the mass in the samples decreased as the moisture content decreased from 0.538 g, 0.188 g, 0.173 g and 0.1741 g for wet parchment coffee beans and dried parchment coffee beans, respectively because it depends on moisture content as reported by Chandrasekar *et al.* (1999). The different studies evaluated the moisture content of cherries ranging from 55-65% wb, pulps (75.9%) parchment with mucilage (55.6%) (Chandrasekar *et al.*, 1999; Ghosh, 2014). In this study, the parchment without mucilage showed a moisture content of 29.9% wb which is in the range (of up to 32% wb) as reported by Chandrasekar *et al.* (1999). Therefore, it has been observed that the well-grown Arabica cherries from high altitudes in tropical regions for example East Africa with 55-65% wb and wet parchment coffee beans with 29.9% wb can predict not affect the performance of the pulping machine. That is the one recommended to keep the better performance of the pulping machine. Thus, the moisture content is a critical parameter to be controlled during the pulping process to avoid high breakage of beans in wet processes performed by using water or not. For example, for the evaluation of depulping Robusta cherries in Nigeria, the cherries were soaked for 3 hrs to increase moisture content because Robusta from hot countries showed lower moisture (Jackson *et al*., 2016).

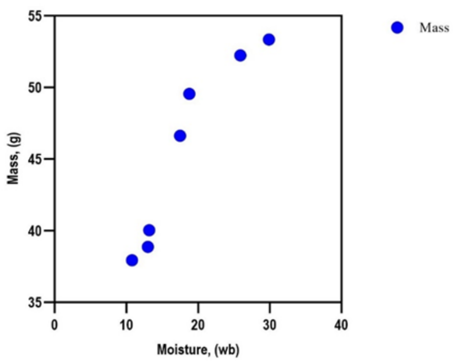

Figure 10. Correlation between moisture, drying time and mass of parchment coffee.

The correlation coefficient of 100 beans' moisture content and mass showed a significant difference at (P-value < 0.007). Comparing the engineering properties of coffee seeds at the moisture content of 10.7% wb that were reported by Adeleke *et al.* (2017); the results obtained in this work are almost similar values of the parameters in their results. The relationship between mass and moisture content reduction in parchment coffee is not linear as shown in Figure 10. The length, width and thickness investigated on Rwandan Arabica cherries showed a significant correlation at a P-value < 0.05. This non-significant difference was found for the dimensions between different districts with the same variable unit such as length to length, width to with and thickness to thickness.

The results showed that there was a slight decrease in dimensions from the wet parchment coffee to the dried ones according to the moisture content reduction. This was confirmed by the mean size determined at the country level that drying beans cannot change the size of parchment. Compared to Malaysian Robusta and Liberica, the mean length (15.40 mm), width (13.03 mm) and thickness (13.03 mm) of Rwandan Arabica cherries were almost similar to the Malaysian Arabica coffee mean length (15.65 mm), width (13.90 mm) and thickness (13.50 mm), larger than of the Robusta mean length (13.90 mm), width (13.90 mm) and thickness (13.90 mm), but smaller than of Liberica coffee length width and thickness (Ismail *et al.*, 2014). The Rwandan dried Arabica coffee beans showed a greater mean size of geometric diameter (7.72 mm), arithmetic diameter (8.25 mm) and equivalent diameter (7.81 mm) compared to the Ethiopian (Jimma) of length (9.90 mm), width (6.92 mm), thickness (4.25), geometric diameter (6.56 mm), arithmetic diameter (6.95 mm) and equivalent diameter (6.71 mm) (Tesfa *et al.*, 2019). The size, density, and volume of both cherries and beans are more important coffee parameters that can help in designing and improving the coffee treatment equipment (pulper) in the post-harvest process, particularly the coffee pulping machine (Ismail *et al.*, 2014). Solely, the size is important in screening and grading coffee beans) (Ismail *et al.*, 2014; *Saparita et al.*, 2019). The Geometric mean, Equivalent and Arithmetic diameters, volume, cross-section area, sphericity, shape index and aspheric ratio calculated based on the size of cherries showed a significant difference. Hence, for designing the hopper, feeder rod of the pulper and setting out clearance between disc and pulping plate, drum and feed plate can be based on the length, width and sphericity of raw cherries.

The mean size of dried parchment coffee from 8 districts showed a greater correlation in length, width and thickness. Figure 11 shows the elements that have significant differences in P-value < 0.05 from 276 comparisons per family conducted in blue colour as perfectly positively correlated (+1) and the ones in red as strongly negatively correlated (-1). Therefore, most dimensions had a correlation coefficient of around 0.5 as shown in yellow colour. The highest correlation and smallest of 0.76 was between length and thickness and the smallest of 0.37 was between width and thickness. The highest correlations obtained were approximately

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0.9, 0.8, and 0.6 between Gakenke width and Kamonyi width, Huye length and Huye thickness, and Nyabihu length and Nyabihu thickness, respectively. Therefore, the correlation in size also helps to understand the contribution of the size in the design and performance of the pulping machines.

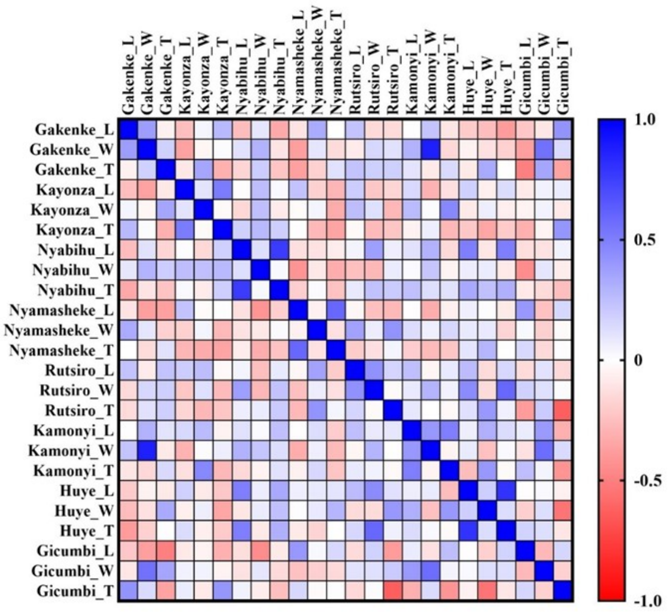

Figure 11. Heat map correlation coefficient of parchment coffee beans from 8 districts of Rwanda at 10.8% wb.

The size of cherries helps directly in determining the volume hopper based on the feed rate of the pulping machine, determining form, size of feeder rod of drum pulper and pulping clearance; setting up a pulping unit to ensure all cherries to be pulped by the machine. From the observation of pulping machine drum, disc and slotted screen pulping units, the size of parchments is the important parameter in designing the size of bulbs, and slots, respectively to allow a parchment to slide in between and be separated from the pulps. The parchments slide on pulping units also depending on their mass gravity, and the mucilage without being clogged as the machine rotates. When the size of the parchment does not match with the settings of pulping clearance, some adjustments can be performed to reduce the breakage rate of the beans. Therefore, knowledge of cherries' size is a key factor in designing hopper and coffee pulping units.

The objective of Principal Component Analysis (PCA) is to reduce the dimension of the data by selecting a subset of principal components. Therefore, the PCA for the dimensions as the key parameter of defining the performance of the pulping machine has been used to check how much the coffees from Rwanda are correlated to a designed machine for the case of Rwanda. It has been observed that coffee cherries from 8 districts are most positively correlated for their length, width and thickness as shown in Figure 12a. After depulping, the wet parchment coffee beans showed less positive correlation compared to the size of cherries as shown in Figure 12b.

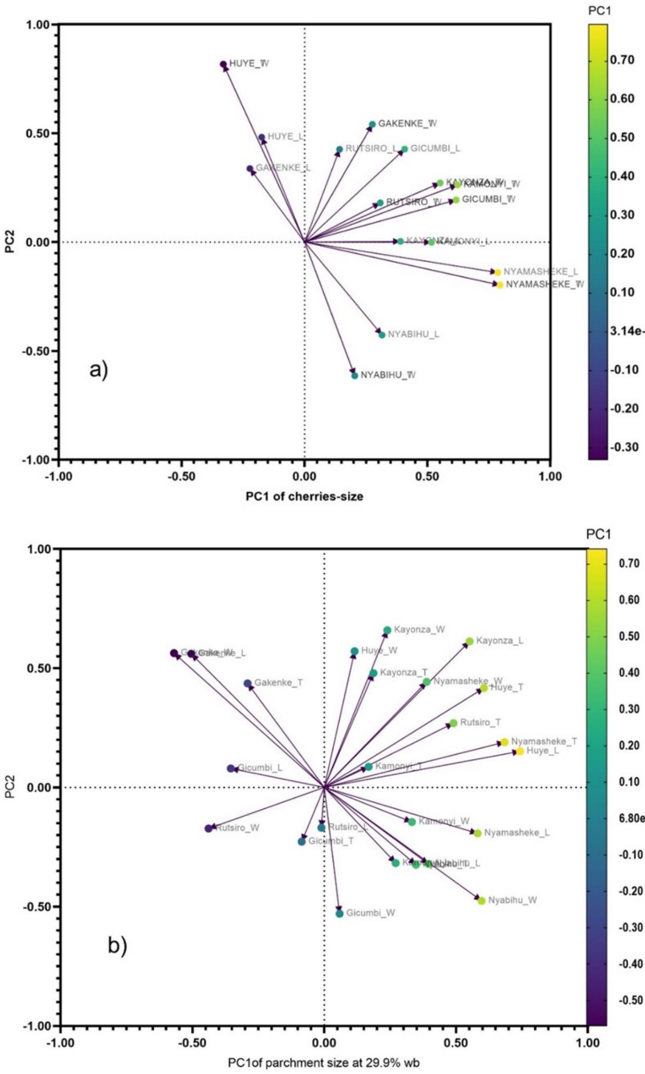

Figure 12. Loading Principal Component Analysis (PCA) a) of cherries and b) wet parchment coffee beans size.

The filling angle was determined 23.33±0.20° and the emptying angle was 38.68±0.39°. The obtained angle revealed a closeness to the angle of repose from the other previous studies (Ismail *et al.*, 2014). These angles define the behaviour of the cherries and beans on the surface of materials usually used in depulping machines. For developing pulping machine hopper, pulping unit and outlet, the angle of repose helps to define the material and the right position of each part to allow coffee to flow with the help of gravity. Therefore, cannot ignore the consideration of the angle of repose in the design of coffee pulping in conformity to the properties of coffee in different areas.

The coefficient of the friction obtained was 0.58±0.03 with the corresponding angle determined at 30.33±1.52°; these parameters define the resistance in the flowing of coffee beans on the surface of a sheet of

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the pulping machine. For example, the angle needed to design the hopper, and the behaviours of beans of how the beans slide in the pulping unit (Ismail *et al.*, 2014; *Saparita et al.*, 2019). Thus, during pulping process, if the resistance becomes high, water can be added to avoid the breakage of the beans. Normally, the co-efficiency of the stainless steel clean and dry is 0.34-0.8 (Ogunjirin *et al.*, 2020) and aluminium of 0.3 to 0.645 (Nwakuba *et al.*, 2019), however, the resistance of the beans on the stainless steel is in the range of that of the other sheets. Therefore, the beans can slide freely on different materials due to the gravity and geometry of pulping unit, since the co-efficiencies are not much different.

The mean fracture force measured to break the Arabica coffee beans was 29.85± 6.813 kgf. This fracture force of 29.85±6.813 kgf obtained for Arabica coffee is greater than that of Arabica (2.451g-f due to different moisture content of 18.76% wb) evaluated in Indonesia and it is about 5 times the rupture force of Liberica bean of 60N in the study conducted in Malaysia (Ismail *et al.*, 2014; Kuala *et al.*, 2019). Knowing this pressure force needed for breaking cherry pulps in tension and shearing and separating the pulp from beans can be based on setting the pulping clearance of the machine. Thus, during the pulping process, the coffee beans can be crushed due to the pressure force between the pulping plates and the drum that squeezes the cherries and removes pulps. To avoid damaging the beans, based on the size of the beans, the clearance in the pulping mechanism should be controlled to avoid breaking of beans.

The frequency of size of the parchment coffee beans for length, width, and thickness was established as shown in Figure 13. The results showed that around 70% of the thickness was 5 mm and 30% had 4.5 mm. The width of the coffee beans showed 8 mm and 8.5 mm with an equal frequency of 50% each. The length also showed 12.5% with 11.5 mm, 50% with 12.0 mm, 25% with 12.5 mm and 12.5% with 13.5 mm. Therefore, it observed that volume, tonnage, and probably the force to rupture depend on the size of cherries or beans (Bizimungu *et al.*, 2022).

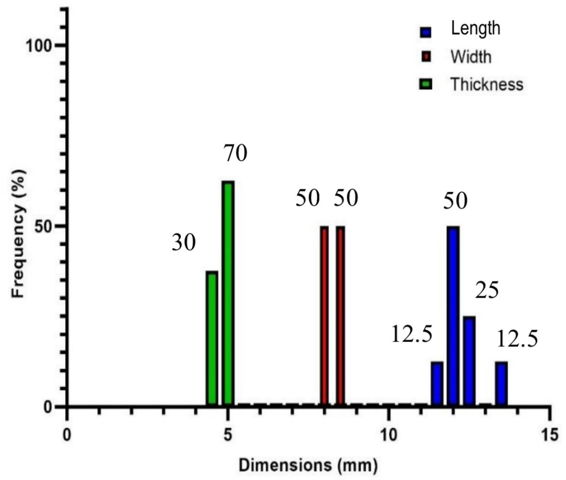

Figure 13. Dimension frequency distribution for the Arabica parchment coffee beans.

After all, the coffee cherries and parchment coffee quality parameters depend on different factors, the accuracy of the instruments used for conducting research, human error, growth factors, geographical conditions, and harvesting period. The last one is critical because the season starts with small cherries size, increases up to the middle, and decreases at the end of the season. From all the above factors, the pulping machine should be designed with the option of adjusting the pulping unit for the whole size of the cherries and parchment coffee beans during the harvesting period (Adeleke *et al.*, 2017). Hence, the efficiency and capacity of the machine do not only depend on the size but also on the maturity of the cherries in each harvested batch (Dalecha and Dibaba, 2018).

5. Conclusion

The physical and mechanical quality parameters of Arabica investigated in Rwanda showed a small difference in size, masses, densities, angle of repose and coefficient of friction based on 8 districts. It was revealed that providing knowledge on the coffee cherries and beans to local manufacturers of pulping machines in the East African region and to the machine importers is the key to improving the performance of coffee pulping machines and producing high-quality coffee beans. Some of the important parameters of coffee to consider when setting up the machines during the pulping process are size, volume, shape index, and fracture force. The parameters that smallholders should consider needed at the market level for exporting coffee are the size, density and colour of the green beans. Therefore, further research is needed to focus on the physicochemical and mechanical properties of Robusta coffee available in Rwanda. The size of cherries varies according to the growth factors; from the current work, it is, therefore, preferable to investigate the quality parameters of coffee throughout the whole harvesting period.

Conflict of interest

The authors declare no conflict of interest for the published results.

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