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Physicochemical profiling of Bambara groundnut (*Vigna subterranea* L.) reveals variation in cooking quality relevant to breeding programs

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Understanding seed physicochemical properties allows breeders to select traits that contribute to desirable cooking characteristics (texture, taste, and nutritional content). Breeding programs can optimize resources by focusing on traits directly related to cooking time and quality. A total of 156 Bambara groundnut (BGN) recombinant inbred lines were analysed for physicochemical properties [hydration capacity (HC), hydration index (HI), swelling index (SI), pH, texture and cooking time (CT)], proximate and nutrient compositions. Analysis of variance showed significant differences ($p < 0.05$) in variables measured. Shortest CT (40 min) was recorded in S19/Ankpa4-100-87, while S19/Ankpa4-106-92 has the longest CT (147 min). Cooking time was negatively correlated with HC ($r = -0.42$), HI ($r = -0.45$) and swelling capacity (SC) ($r = -0.55$). Neutral Detergent Fibre (NDF) and protein content showed significant differences between raw and cooked BGN ($p < 0.05$). Cooking significantly increased protein, fat, NDF, Zn, and Cu; however, cooking also significantly reduced Fe and total mineral (ash). Texture, CT and electrical conductivity (EC) of the genotypes varied significantly, which aided classification into five groups, namely: A (soft-cooking genotypes), B (slightly soft-cooking genotypes), C (slightly hard-cooking genotypes), D (moderately hard-cooking genotypes) and E (hard-cooking genotypes). A total of 14 genotypes (DodR, BURKINA, ANKPA 4, TIGD, NAV 4, S19/Ankpa4-100-87 IITA686/LunT-292-233, IITA686/LunT, S19/Ankpa4-130-1, S19/Ankpa4-50-43, S19/Ankpa4-92, IITA686/LunT-403-314, S19/Ankpa4-141-121 and S19/Ankpa4-234-197) were grouped as soft-cooking. These soft-cooking genotypes could be available as genetic stock to confirm this attribute or reanalysis by breeders.

Keywords Cooking time, Hard-to-cook, Nutrition, Recombinant inbred lines (RILs), Underutilised crops, Vision for adapted crops and soils (VACS)

Bambara groundnut (BGN) (*Vigna subterranea* L. Verdc) is a sustainable and affordable source of carbohydrates, protein, unsaturated fatty acids, and essential minerals (magnesium, iron, zinc, and potassium)[1]. Often cultivated

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by women, this legume crop is primarily grown to nourish their families[2]. Bambara groundnut seeds contain approximately 64% carbohydrates, 23.6% protein, 6.5% fat, and 5.5% fibre[3]. Tan, Azam-Ali[1] reported BGN to be rich in Fe (4.9–40 mg 100 g^{-1}), Ca (95.5–99 mg 100 g^{-1}), K (11.44–19.35 mg 100 g^{-1}), and Na (2.9–12 mg 100 g^{-1}). Apart from their nutritional value, BGN has been found to contain polyphenolic compounds, suggesting their potential as nutraceuticals[4,5].

Pregnant and lactating women, along with young children, are particularly vulnerable to micronutrient deficiencies due to high nutrient demands for reproduction and growth[6]. Legumes like BGN can play a pivotal role in bridging this nutritional gap, especially in low-income settings. Despite its nutritional richness, BGN remains underutilised in Africa due to undesirable cooking quality traits, notably the hard-to-cook (HTC) trait[7].

Cooking quality is increasingly considered a critical parameter in legume improvement programs, influencing consumer acceptance and energy requirements during preparation[8,9]. Key metrics for assessing cooking quality include cooking time, cooking loss, water absorption index, swelling index, and textural properties[10], yet many studies assess these traits in isolation or using limited genotypic diversity. Breeding programs in the Global South must prioritise cooking quality improvement to promote greater adoption and utilisation of climate-resilient crops like BGN.

Cooking quality of legume seeds has garnered significant attention due to its implications on nutrition and energy consumption, making it a focal point for consumers, manufacturers, and researchers[11,12]. The cooking process involves applying heat to food items, making grain legumes more tender and palatable enhancing their nutritional quality[13,14]. Most grain legumes are soaked before cooking to ensure uniformity during the expansion of the seed coat and to reduce cooking time, thereby influencing texture[14,15].

However, hard-to-cook (HTC) legumes pose a significant obstacle to consumption, prolonging cooking time and requiring more energy[16]. Water absorption, an indirect criterion used to determine cooking quality, is linked to seed hydration capacity and the HTC phenomenon[17–19]. Additionally, morphological traits such as seed coat thickness and flatness correlate with cooking time, indicating a genetic influence on cooking quality[20]. Instrumental texture analysis has emerged as a valuable method for evaluating legume hardness, aiding in high-throughput phenotyping[21]. Cooking time, a heritable trait, varies among genotypes, underlining its importance in breeding programs to improve cooking and nutritional quality[22,23].

While cooking improves nutrient availability, prolonged cooking may decrease nutrient retention, highlighting the need for optimal cooking times[8]. Despite the importance of cooking quality traits, they are relatively overlooked in crop improvement programs, creating a gap in the management of HTC[16]. Short-cooking varieties of BGN hold promise to increase consumption, reduce energy usage, and address food and nutrition insecurity, particularly in rural areas[11,12]. Collaborative efforts between plant breeders and nutrition experts are crucial for developing BGN varieties that are nutritionally superior and possess cooking characteristics consumers prefer[11,12].

Hence, this study assessed the cooking quality and nutritional diversity among Bambara groundnut recombinant inbred lines. Integrating cooking quality traits with nutritional profiling across genetically diverse RILs presents a novel approach to inform breeding decisions. These findings will inform the selection of superior genetic stock for breeding programs targeting the improvement of HTC traits.

Materials and methods
Plant material
This study used 135 BGN F6 lines and 21 landraces from the University of Nottingham Malaysia to capture a broad genetic spectrum. The F6 lines were derived from two crosses, S19/Ankpa 4 and IITA686/LunT (Fig. 1). Variations are observed in seed coat colour, size, and lustre, ranging from dark purple and black to cream, red, and speckled brown. A millimetre scale beneath each set of seeds provides a visual reference for size comparison. The BGN seeds were manually harvested and sun-dried at Ukulinga Research Farm, Pietermaritzburg, South Africa. The seeds were stored for one month at 25 °C before conducting experiments. Figure 2 summarizes all the experimental procedures and collected data for the study.

Seed physicochemical properties
The seed size, volume and density were determined as described by[24–26], respectively. Seed hydration and swelling properties were measured according to Yadav, Singh[27]. Fifty seeds per genotype and 100 ml of deionised H$_2$O were added to the Erlenmeyer flask and left for 16 h at 25 °C. Seed weight and volume were measured before and after soaking to calculate hydration and swelling properties. Leached electrolytes and pH were determined using the method described by[28]. Hunter Lab colorimeter (Hunter Associates Laboratory Inc, Reston, VA) was used to measure the seed coat colour of raw BGN seeds. The seed colour was measured as L*, a*, b*, according to an international standard Commission Internationale d'Eldarage (CIE) adopted. Seeds were enclosed in a glass cup topped with a metal cup for colour measurement and shaken to minimize sampling error caused by colour variation among seeds. The process was repeated in triplicate in each sample.

Preparation of Bambara groundnut samples for cooking
Each sample of BGN seeds was measured using a 25 ml glass cup separately, and the quantity of the BGN seeds depended on the seed size. The BGN seeds were placed in a pot containing 200 ml deionised water and boiled on a Defy Thermofan Stove (Model 731 MF) at heat setting 5. Cooking time for each BGN was recorded. Cooking time was from boiling until 90% of the seeds were cooked. The visual determination of gelatinisation and finger-pressing methods were used to determine the cooking level. The cooked BGN seeds were pressed between the thumb, and the forefinger and seed were recorded as cooked when cotyledons disintegrated upon pressing[29]. The samples were withdrawn from the pot without interrupting boiling, and the degree of cooking was tested at five-minute intervals. This procedure was repeated until all samples of BGN were classified as cooked. Seeds
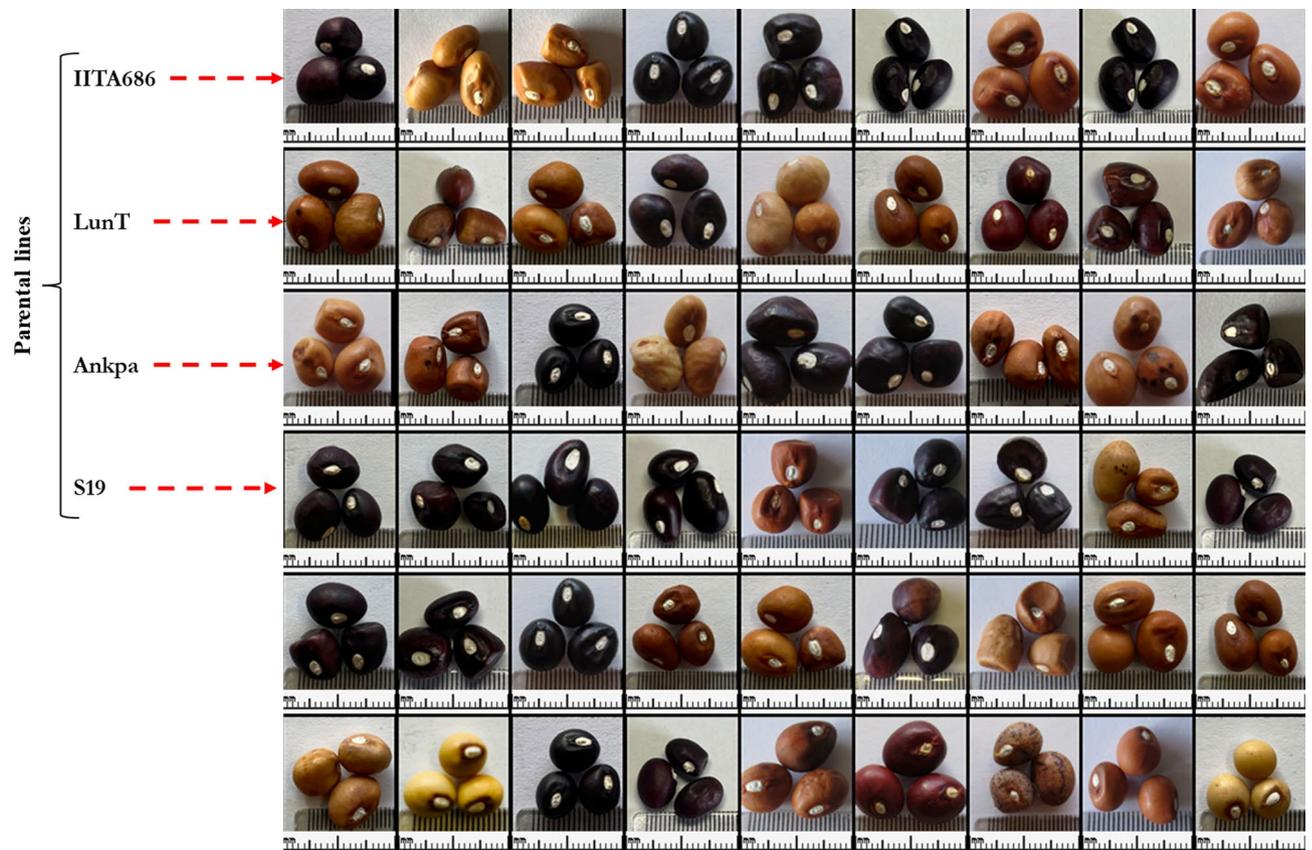
Fig. 1. A visual sample of Bambara groundnut seed material used in the study, including IITA686, LunT, Ankpa and S19 with multiple morphotypes.

were considered cooked when five consecutive tested seeds were cooked, and at this time, total cooking time was recorded.

Texture analysis of cooked seeds

Once the samples were cooked, the texture of the BGN was determined using the Texture Analyser TA-TX2 (Stable Microsystem, Surrey, England). A return-to-start method was used to measure force under compression using a Warner-Bratzler shear cell. A 2 mm probe was used to record the maximum peak force. The BGN seeds were axially compressed to 75% of their original height. The force-time curves were recorded at a speed of 2 mm/s, and the results were expressed in Newton (N).

Nutritional analysis

Ten samples with the shortest and longest cooking times were selected for nutritional analysis. The raw and cooked samples were freeze-dried and ground to a fine powder using a coffee grinder model CBM4-B5. Five grams of fine powder per sample were taken to the Analytic Services Department at Cedara College of Agriculture for nutritional analysis (moisture, ash, fat, fibre, crude protein, and total mineral content).

Elemental analysis (Ca, Cu, Fe, K, Mg, Mn, and Zn) was done using Fast Sequential Absorption Spectrometer (Varian AA280FS) interfaced with SpectrAA version 5.1 PRO software. The AAS was calibrated using an ICP multi-element standard solution IV, prepared within the optimal working range (0–100 ppm) for FAAES, following the protocol outlined by Mandizvo, Odindo[30]. Flame conditions were standardized by adjusting the airflow to 12 L/min and acetylene gas flow to 8 L/min. A hollow cathode lamp specific to each element was stabilized for 5 min and optimized for maximum emission intensity. Instrumental zero was established by aspirating a 5% HNO_3 blank into the flame. Sensitivity was fine-tuned using working standard solutions to achieve full-scale deflection of the galvanometer. Each sample solution was aspirated in triplicate, and the mean absorbance values were recorded. Elemental concentrations were determined by interpolating absorbance values from standard calibration curves. Final concentrations in the original samples were calculated following Kurilenko and Kostyreva[31], based on the mass of the sample and the volume of the digest solution, as illustrated in Eq. (1).

$$\text{Final conc. (mg/l)} = \text{Average} \times \frac{\text{volume (25 ml)}}{\text{mass (0.2 g)}} \tag{1}$$
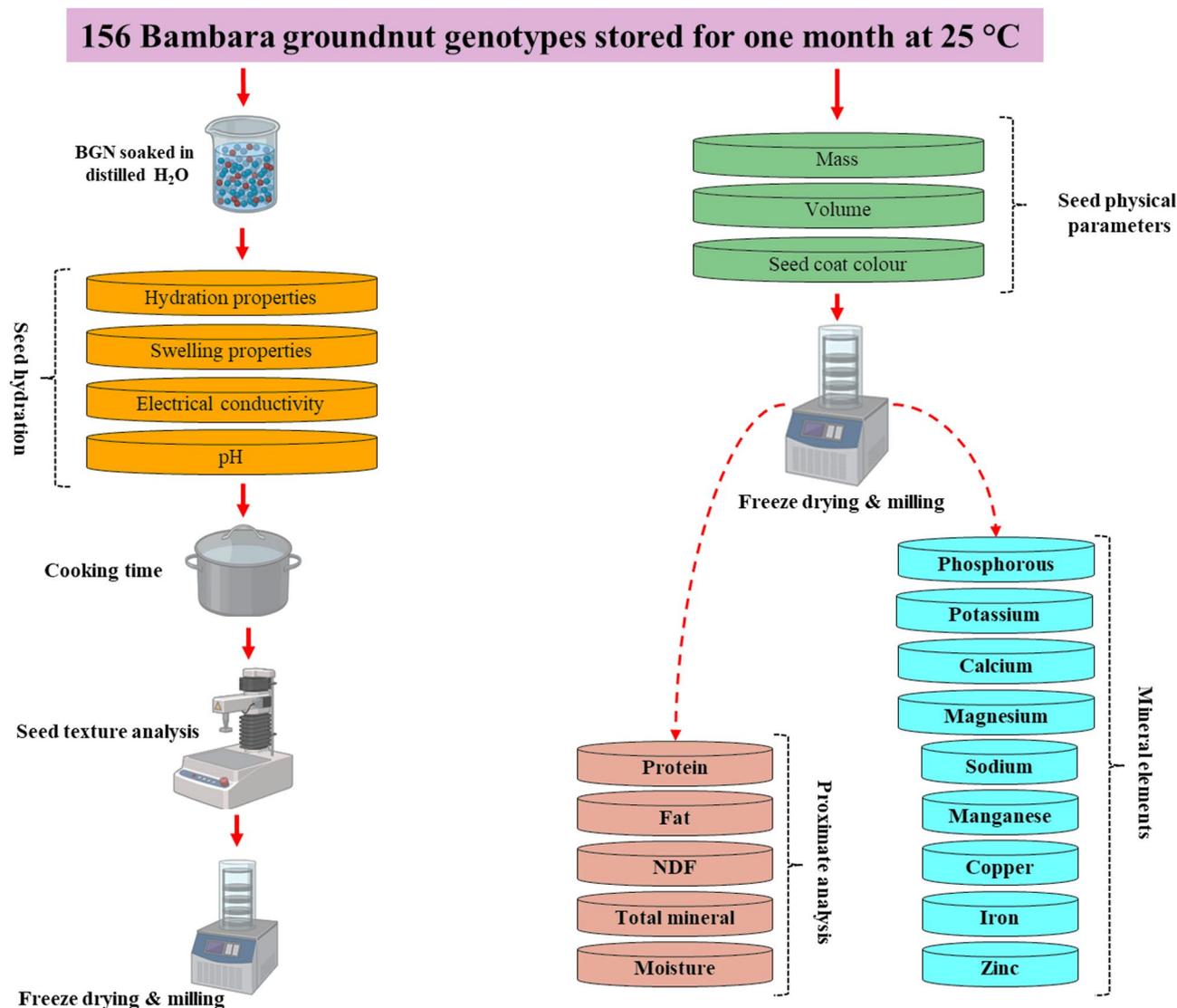
Fig. 2. Flow chart illustrating experimental methodology from seed storage to nutritional analysis.

Statistical analysis

Data collected were subjected to analysis of variance (ANOVA) using GenStat statistical analysis software 23rd edition (VSN International, Hempstead, UK). Means were separated using Fisher's protected least significant difference (LSD) when treatments showed significant differences at 5% level of probability. Correlation analysis was performed to determine associations among Bambara groundnut physicochemical properties using the *corrplot* package in R version 4.0 (R Core Team, 2023). Principal component analysis (PCA) was performed using the correlation matrix using XLSTAT (XLSTAT 2023.5.1.1075). A paired t-test was performed to identify statistical significance between the raw and cooked nutritional composition of BGN. Agglomerative Hierarchical Clustering (AHC) was performed using cooking time and texture according to Ward's method using squared Euclidean distance to measure similarity using ORIGINPRO ® 2024 software.

Results

Physicochemical properties

The ANOVA revealed significant differences in physicochemical properties among the 156 Bambara groundnut accessions ($P < 0.001$), indicating highly significant variation (Table 1). The ANOVA test suggests substantial differences in the measured physicochemical properties across the diverse array of Bambara groundnut accessions studied, highlighting the inherent variability within this species.

For seed size (SS), accessions UNISWA, S19/Ankpa4-65-56, S19/Ankpa4-136-116, IITA686/LunT-419-324 and S19/Ankpa4-199-169 had highest SS (≥ 0.750 g). Conversely, accessions such as S19/Ankpa4-106-92, ANKPA 4, IITA686/LunT-370-288 and S19/Ankpa4-112-96 had lowest SS (≤ 0.330 g). Highest seed volume (SV) values (≥ 0.630 ml) were recorded in S19/Ankpa4-136-116, UNISWA, S19/Ankpa4-199-169 and S19/

S.O.V	d.f	SS	SV	ρ	HC	HI	SC	SI
Genotype	155	0.031**	0.021**	0.085**	0.021**	0.113**	0.023**	0.208**
Residual	312	4.474×10^{-4}	3.321×10^{-4}	4.773×10^{-4}	4.000×10^{-6}	1.974×10^{-4}	4.000×10^{-6}	1.315×10^{-6}
Total	467	–	–	–	–	–	–	–
S.O.V	d.f	CT	EC	pH	L*	a*	b*	Texture
Genotype	155	1035.710**	3.801**	$1.552 \times 10^{0**}$	526.215**	118.162**	$4.019 \times 10^{2**}$	92.925**
Residual	312	13.950**	0.622	9.000×10^{-4}	1.736	1.269	1.000×10^{-6}	1.440
Total	467	–	–	–	–	–	–	–

Table 1. Analysis of variance showing mean squares and significant tests for seed physicochemical properties of 156 Bambara groundnut accessions. *S.O.V* source of variation; *d.f* degrees of freedom; *SS* seed size; *SV* seed volume; *ρ* density; *HC* hydration capacity; *SC* swelling capacity; *SI* swelling index; *CT* cooking time; *EC* electrical conductivity; *pH* potential of hydrogen; *L** lightness from black to white on a scale of zero to 100; *a** and *b** chromaticity with no specific numeric limits.

Ankpa4-21-19. Lowest SV values (≤ 0.270 ml) were recorded in IITA686/LunT-387-301, IITA686/LunT-403-314, NAV 4, S19/Ankpa4-96-84 and S19/Ankpa4-112-96 (Table 2).

Seed density (ρ) was highest in S19/Ankpa4-130-112, S19/Ankpa4-18-17 and S19/Ankpa4-67-58 (≥ 1.670 g ml^{-1}). Lowest ρ (≤ 1.050 g ml^{-1}) was recorded in S19/Ankpa4-247-208, S19/Ankpa4-139-119, IITA686/LunT-365-284 and S19/Ankpa4-49-42. The hydration capacity (HC) was highest (≥ 0.370 ml g^{-1}) in BURKINA, S19/Ankpa4-92-79, DodR, and TIGD, and lowest (≤ 0.010 ml g^{-1}) in IITA686/LunT-301-240, IITA686/LunT-365-284, IITA686/LunT-420-325, S19/Ankpa4-125-107, S19/Ankpa4-188-159, S19/Ankpa4-253-213, and S19/Ankpa4-73-64 (Table 2).

Highest values (≥ 0.840) for hydration index (HI) were recorded in BURKINA, NAV 4, TIGD and ANKPA 4 while lowest HI (≤ 0.020) was recorded in IITA686/LunT-301-240, IITA686/LunT-420-325, S19/Ankpa4-125-107, S19/Ankpa4-188-159, S19/Ankpa4-253-213 and S19/Ankpa4-73-64. Swelling capacity (SC) ranged from 0.020 to 0.470; the highest SC was recorded in BURKINA (0.470), and lowest SC (≤ 0.020) was recorded in S19/Ankpa4-235-198, S19/Ankpa4-253-213, S19/Ankpa4-88-76 and UNISWA (Table 2).

Swelling index (SI) was highest in IITA686/LunT-403-314, BURKINA, TIGD and NAV 4 (≥ 1.110). Lowest SI was recorded in UNISWA (0.030). Longest cooking time (CT) (≥ 120 min) was recorded in eight accessions namely, S19/Ankpa4-106-92, SONGKHLA, S19/Ankpa4-89-76, UNISWA, S19/Ankpa4-171-143, GHC37105, DIP-C and MOQ-4. Shortest (CT) (≤ 60 min) was recorded in eleven accessions namely, IITA686/LunT-427-330, DodR, ANKPA 4, BURKINA, S19/Ankpa4-141-121, S19/Ankpa4-234-197, IITA686/LunT-403-314, TIGD, S19/Ankpa4-92-79, NAV 4 and S19/Ankpa4-100-87 (Table 2).

S19/Ankpa4-106-92, SONGKHLA, S19/Ankpa4-89-76, GHC37105 and UNISWA recorded highest electrical conductivity (EC) (≥ 9.280 kΩ cm^{-1}). Lowest EC (≤ 5.380 kΩ cm^{-1}) was recorded in IITA686/LunT-403-314, TIGD, S19/Ankpa4-92-79, NAV 4, IITA686/LunT-337-264 and S19/Ankpa4-100-87. Highest pH values (≥ 8.140) were recorded in S19/Ankpa4-100-87, NAV 4, S19/Ankpa4-92-79, TIGD, S19/Ankpa4-130-112 and BURKINA. Lowest pH values (≤ 5.580) were recorded in IITA686/LunT-334-262, MOQ-4, S19/Ankpa4-89-76, S19/Ankpa4-171-143, UNISWA, SONGKHLA and S19/Ankpa4-106-92 (Table 2).

Seed texture ranged from 5.40 to 32.70 N, with highest texture values (≥ 28 N) recorded in S19/Ankpa4-106-92, SONGKHLA, S19/Ankpa4-171-143, S19/Ankpa4-89-76, UNISWA and GHC37105. Lowest texture values (≤ 8 N) were recorded in S19/Ankpa4-141-121, IITA686/LunT-403-314, S19/Ankpa4-92-79, TIGD, NAV 4 and S19/Ankpa4-100-87.

Data visualisation

Figure 3 provides insights into the underlying distribution of the data observed. Figure 3a,h,l depict symmetrical violin plots representing SS, CT, and texture data. The density is balanced on both median sides, creating a mirror-like appearance. In these violin plots, the density of the data is evenly distributed around the median, leading to a balanced, mirror-like shape on both sides of the plot. This symmetry indicates that the data points are spread out equally on either side of the median value, suggesting that SS, CT, and texture distributions are not skewed in any direction. Instead, they exhibit a central tendency where the data is clustered around the median. By observing the balanced density in these violin plots, we can infer that the central measure (median) is a good representative of the dataset for SS, CT, and texture. This symmetry also suggests that any statistical analyses or modelling approaches applied to these datasets will likely yield reliable and meaningful results, given the normal-like distribution of the data.

Figure 3c,d,e,f,g depict skewed violin plots representing ρ, HC, HI, SC and SI, respectively. There is a noticeable imbalance in the density of data points on one side compared to the other, suggesting that the data distribution is skewed, with more data points concentrated on one side of the median. In contrast to the symmetrical violin plots seen in Fig. 3a,h,l, the violin plots in Fig. 3c–g display an evident imbalance in the density of data points between the two sides of the median. This disparity suggests that the data distribution is skewed, with a greater concentration of data points observed on one side of the median than the other.

Figure 3b,i,j depict bimodal violin plots representing SV, EC and pH, respectively. There are two distinct peaks or modes, indicating the presence of two separate groups or clusters within the dataset. This suggests that the data may comprise two distinct populations or categories. Identifying bimodal distributions is crucial as it

Genotype name (code)	SS (g)	SV (ml)	ρ (g ml⁻¹)	HC (ml g⁻¹)	HI	SC	SI	CT (mins)	EC (kΩ cm⁻¹)	pH	L*	Texture (N)
100SB16ANAM-C (E1)	0.58^{ghijklm}	0.47^{de}	1.23^{stuvwxy}	0.08^{x}	0.14^{ABCDEF}	0.07 L	0.15^{DE}	91^{qrstuvwxyzAB}	7.79^{abcdefghijklmnopqrst}	7.09^{OPQ}	33.56^{wxyz}	19.3^{stuvwxyzABCDEFGHIJKL}
20ACC118ivb (E2)	0.64^{efgh}	0.5^{d}	1.28^{mnopqrst}	0.1^{v}	0.16^{yzABCD}	0.13i	0.26^{xy}	93^{pqrstuvwxyz}	7.82^{abcdefghijklmnopqrs}	6.83^{UVWXY}	18.3^{JKLMNOPQRSTUVWX}	19.9^{qrstuvwxyzABCDEFGHI}
ANKPA 4 (E3)	0.32^{EF}	0.3^{ij}	1.07^{FGHIJ}	0.27^{h}	0.84^{ab}	0.27e	0.9^{e}	56^{QRSTU}	5.47^{pqrstuvw}	8.11^{e}	40.3^{rs}	8.4^{efghi1ij1kl}
BURKINA (E4)	0.47^{qrsturwx}	0.33^{hij}	1.42^{ghij}	0.42^{a}	0.89^{a}	0.47a	1.42^{b}	56^{QRSTU}	5.41^{qrstuvw}	8.14^{de}	57.81^{a}	8.4^{efghi1ij1kl}
DIP-C (E5)	0.71^{cde}	0.5^{d}	1.42^{ghij}	0.22^{j}	0.31^{op}	0.23f	0.46^{q}	121^{bcde}	9.24^{abcde}	5.99^{i1}	47.58^{defghijklm}	27.9^{bcde}
DodR (E6)	0.67^{def}	0.57^{bc}	1.18^{wxyzABC}	0.38^{c}	0.57^{h}	0.37c	0.65^{k}	59^{PQRST}	5.66^{opqrstuvw}	7.99^{fgh}	30.09^{xyzABCD}	9.1^{d1efghi1ij1kl}
EXSOCOTO (E7)	0.54^{klmnopq}	0.5^{d}	1.08^{EFGHIJ}	0.16^{p}	0.3^{pq}	0.1k	0.2^{AB}	113^{defghij}	8.89^{abcdefghi}	6.35^{p1q1r1}	50.56^{cdefg}	26.7^{bcdefgh}
GHC37105 (E8)	0.57^{hijklmn}	0.47^{de}	1.21^{stuvwxyzA}	0.13^{s}	0.23^{stuvw}	0.03n	0.06^{KL}	123^{bcde}	9.28^{abcd}	5.62^{w1x1}	19.04^{JKLMNOPQRSTUVW}	28^{bcd}
IITA686 (E9)	0.58^{ghijklm}	0.47^{de}	1.23^{stuvwxy}	0.15^{q}	0.26^{pqrst}	0.17 h	0.36^{tu}	86^{tuvwxyzABCDE}	6.61^{cdefghijklmnopqrst}	6.91^{STUV}	19.77^{JKLMNOPQRSTUVW}	17.3^{DEFGHIJKLMNOPQRS}
IITA686/LunT-257-216 (E10)	0.53^{lmnopqr}	0.4^{fg}	1.36^{jklm}	0.08^{x}	0.15^{zABCDE}	0.07 L	0.18^{C}	113^{defghij}	8.84^{abcdefghi}	5.88^{s1t1}	50.62^{bcdefg}	23.5^{efghijklmnopqrst}
IITA686/LunT-260-219 (E11)	0.44^{tuvwxyz}	0.37^{fgh}	1.19^{uvwxyzAB}	0.12^{t}	0.27^{pqrs}	0.1k	0.27^{x}	77^{CDEFGHIJKL}	6.61^{cdefghijklmnopqrst}	7.25^{FGHIJKL}	39.41^{stuv}	14.9^{LMNOPQRSTUVWXYZa1}
IITA686/LunT-261-220 (E12)	0.35^{BCDE}	0.3^{ij}	1.17^{wxyzABCD}	0.22^{j}	0.63^{g}	0.2 g	0.67^{j}	65^{LMNOPQR}	5.93^{klmnopqrstuvw}	7.86^{jk}	39.38^{stuv}	10.6^{a1b1c1d1e1f1g1h1i1}
IITA686/LunT-262-221 (E13)	0.46^{stuvwxy}	0.4^{fg}	1.15^{yzABCDEF}	0.14^{r}	0.3^{pq}	0.13i	0.16^{D}	78^{BCDEFGHIJKL}	5.99^{klmnopqrstuvw}	7.39^{yzABCD}	48.42^{defghij}	15.1^{KLMNOPQRSTUVWXYZ}
IITA686/LunT-265-223 (E14)	0.51^{mnopqrst}	0.43^{ef}	1.19^{uvwxyzAB}	0.07^{y}	0.18^{wxyzAB}	0.07 L	0.16^{D}	81^{yzABCDEFGHIJ}	7.11^{abcdefghijklmnopqrstuvw}	7.67^{pqrst}	15.95^{PQRSTUVWX}	16.2^{FGHIJKLMNOPQRSTUVW}
IITA686/LunT-284-230 (E15)	0.48^{pqrstuvw}	0.37^{fgh}	1.3^{lmnopqr}	0.03^{C}	0.06^{IJKLM}	0.07 L	0.19^{BC}	103^{ijklmnop}	8.44^{abcdefghijklmno}	6.41^{m1n1o1p1q1}	18.63^{JKLMNOPQRSTUVWX}	23.1^{fghijklmnopqrstuv}
IITA686/LunT-292-233 (E16)	0.49^{opqrstuv}	0.4^{fg}	1.26^{opqrstuv}	0.2^{l}	0.41^{klm}	0.2 g	0.5^{p}	62^{MNOPQRS}	5.83^{mnopqrstuvw}	7.9^{hij}	45.75^{efghijklmno}	10^{c1d1e1f1g1h1i1j1}
IITA686/LunT-293-234 (E17)	0.42^{uvwxyzAB}	0.3^{ij}	1.4^{hijk}	0.1^{v}	0.24^{rstuv}	0.1k	0.33^{v}	70^{HIJKLMNO}	6.25^{ghijklmnopqrstuvw}	7.79^{klmno}	51.06^{bcde}	12.4^{VWXYZa1b1c1d1e1f1}
IITA686/LunT-295-235 (E18)	0.57^{hijklmn}	0.47^{de}	1.21^{stuvwxyzA}	0.02^{D}	0.04^{KLM}	0.02o	0.04^{MN}	101^{jklmnopqr}	8.29^{abcdefghijklmnopqr}	6.48^{1k11m1n1o1}	19.21^{JKLMNOPQRSTUVW}	22^{klmnopqrstuvwxyzAB}
IITA686/LunT-296-236 (E19)	0.45^{stuvwxyz}	0.37^{fgh}	1.23^{stuvwxyz}	0.11^{u}	0.24^{stuv}	0.1k	0.27^{x}	70^{HIJKLMNOP}	6.25^{ghijklmnopqrstuvw}	7.89^{hij}	49.69^{cdefgh}	12.6^{UVWXYZa1b1c1d1e1}
IITA686/LunT-300-239 (E20)	0.42^{uvwxyzAB}	0.33^{hij}	1.27^{nopqrstu}	0.13^{s}	0.31^{op}	0.13i	0.39^{s}	84^{wxyzABCDEFG}	7.23^{abcdefghijklmnopqrstuvw}	7.37^{yzABCDE}	31.92^{wxyzABC}	17.8^{ABCDEFGHIJKLMNOPQR}
IITA686/LunT-301-240 (E21)	0.47^{qrstuvwx}	0.4^{fg}	1.175^{wxyzABC}	0.01^{E}	0.02^{M}	0.02o	0.05^{LM}	94^{nopqrstuvwxy}	7.94^{abcdefghijklmnopqrs}	6.87^{TUVWX}	46.29^{efghijklmno}	20.2^{pqrstuvwxyzABCDEFG}
IITA686/LunT-305-243 (E22)	0.49^{opqrstuv}	0.4^{fg}	1.26^{opqrstuv}	0.08^{x}	0.16^{yzABCD}	0.07 L	0.18^{C}	87^{stuvwxyzABCD}	7.4^{abcdefghijklmnopqrstuv}	7.14^{LMNOP}	44.59^{jklmnopqr}	18.4^{xyzABCDEFGHIJKLMNOP}
IITA686/LunT-314-249 (E23)	0.46^{stuvwxy}	0.4^{fg}	1.53^{cdef}	0.07^{y}	0.15^{zABCDE}	0.17 h	0.57^{m}	71^{GHIJKLMNO}	6.36^{defghijklmnopqrstuvw}	7.79^{klmno}	48.75^{defghi}	12.5^{UVWXYZa1b1c1d1e1}
IITA686/LunT-330-259 (E24)	0.48^{pqrstuvw}	0.4^{fg}	1.2^{tuvwxyzAB}	0.19^{m}	0.4^{lm}	0.1k	0.25^{y}	86^{tuvwxyzABCDE}	7.33^{abcdefghijklmnopqrstuvw}	7.25^{FGHIJKL}	21.56^{HIJKLMN}	18.3^{xyzABCDEFGHIJKLMNOPQ}
IITA686/LunT-332-260 (E25)	0.6^{fghijkl}	0.5^{d}	1.2^{tuvwxyzAB}	0.05^{A}	0.08^{GHIJKL}	0.07 L	0.14^{EF}	68^{JKLMNOPQR}	5.93^{klmnopqrstuvw}	7.9^{hij}	17.22^{MNOPQRSTUVWX}	11.5^{YZa1b1c1d1e1f1g1}
IITA686/LunT-334-262 (E26)	0.62^{fghij}	0.5^{d}	1.24^{qrstuvwx}	0.03^{C}	0.05^{JKLM}	0.02o	0.04^{MN}	118^{cdefg}	8.9^{abcdefghi}	5.58^{x1y1}	39.73^{rst}	26.4^{bcdefghijk}
IITA686/LunT-337-264 (E27)	0.45^{stuvwxyz}	0.37^{fgh}	1.22^{rstuvwxyz}	0.18^{n}	0.4^{lm}	0.23f	0.62^{l}	77^{CDEFGHIJKL}	4.49^{w}	7.38^{yzABCD}	21.66^{HIJKLM}	14.9^{LMNOPQRSTUVWXYZa1}
IITA686/LunT-341-268 (E28)	0.57^{hijklmn}	0.5^{d}	1.14^{zABCDEFG}	0.06^{z}	0.11^{DEFGHI}	0.03n	0.06^{KL}	82^{xyzABCDEFGHI}	7.18^{abcdefghijklmnopqrstuvw}	6.91^{STUV}	20.47^{JKLMNOPQ}	17.7^{BCDEFGHIJKLMNOPQR}
IITA686/LunT-348-271 (E29)	0.45^{stuvwxyz}	0.4^{fg}	1.13^{ABCDEFGH}	0.05^{A}	0.11^{DEFGHI}	0.03n	0.08^{JJ}	91^{qrstuvwxyzAB}	7.78^{abcdefghijklmnopqrst}	6.52^{h1i1j1k1l1m1}	45.78^{efghijklmno}	19.4^{stuvwxyzABCDEFGHIJK}
IITA686/LunT-356-277 (E30)	0.35^{BCDE}	0.3^{ij}	1.17^{wxyzABCD}	0.17^{o}	0.49^{ij}	0.17 h	0.57^{m}	79^{ABCDEFGHIJ}	7.55^{abcdefghijklmnopqrstu}	7.56^{uv}	23.03^{GHIJK}	15.7^{HIJKLMNOPQRSTUVWXY}
IITA686/LunT-357-278 (E31)	0.56^{ijklmn}	0.47^{de}	1.19^{uvwxyzAB}	0.06^{z}	0.11^{DEFGHI}	0.12j	0.25^{y}	117^{cdefgh}	8.91^{abcdefgh}	5.68^{y1w1x1}	42.93^{lmnopqrs}	26.6^{bcdefghi}
IITA686/LunT-360-280 (E32)	0.41^{wxyzABC}	0.3^{ij}	1.37^{ijkl}	0.06^{z}	0.15^{zABCDE}	0.07 L	0.23^{z}	95^{nopqrstuvw}	7.83^{abcdefghijklmnopqrs}	6.83^{UVWXY}	44.57^{jklmnopqr}	20.4^{pqrstuvwxyzABCDEF}
IITA686/LunT-362-281 (E33)	0.47^{qrstuvwx}	0.3^{ij}	1.57^{cd}	0.18^{n}	0.4^{lm}	0.1k	0.33^{v}	75^{CDEFGHIJKLM}	6.61^{cdefghijklmnopqrst}	7.69^{pqrs}	13.92^{X}	14.9^{EFGHIJKLMNOPQRSTUVWXYZa1}
IITA686/LunT-365-284 (E34)	0.4^{xyzABCD}	0.4^{fg}	1^{I}	0.01^{E}	0.03^{LM}	0.02o	0.05^{LM}	100^{klmnopqrs}	8.29^{abcdefghijklmnopqr}	6.51^{i1j1k1l1m1n1}	46.21^{efghijklmno}	22.1^{jklmnopqrstuvwxyzAB}
IITA686/LunT-366-285 (E35)	0.48^{pqrstuvw}	0.4^{fg}	1.2^{tuvwxyzAB}	0.05^{A}	0.1^{EFGHIJ}	0.02o	0.05^{LM}	103^{ijklmnop}	8.42^{abcdefghijklmno}	6.39^{o1p1q1}	15.8^{QRSTUVWX}	22.3^{hijklmnopqrstuvwxy}
IITA686/LunT-367-286 (E36)	0.62^{fghij}	0.5^{d}	1.24^{qrstuvwx}	0.09^{w}	0.15^{zABCDE}	0.13i	0.26^{xy}	98^{lmnopqrstu}	8.03^{abcdefghijklmnopqrs}	6.51^{i1j1k1l1m1n1}	17.06^{MNOPQRSTUVWX}	24.5^{cdefghijklmnop}
IITA686/LunT-370-288 (E37)	0.32^{EF}	0.3^{ij}	1.07^{FGHIJ}	0.1^{v}	0.31^{op}	0.03n	0.26^{xy}	70^{HIJKLMNO}	6.29^{fghijklmnopqrstuvw}	7.59^{stuv}	39.63^{stu}	12.3^{VWXYZa1b1c1d1e1f1}
IITA686/LunT-379-295 (E38)	0.39^{yzABCDE}	0.33^{hij}	1.18^{wxyzABC}	0.22^{j}	0.56^{h}	0.2 g	0.6^{l}	81^{yzABCDEFGHIJ}	6.19^{ghijklmnopqrstuvw}	7.08^{PQR}	16.86^{MNOPQRSTUVW}	16.3^{EFGHIJKLMNOPQRSTUV}
IITA686/LunT-386-300 (E39)	0.45^{stuvwxyz}	0.4^{fg}	1.16^{xyzABCDE}	0.08^{x}	0.18^{wxyzAB}	0.02o	0.05^{LM}	94^{nopqrstuvwy}	7.94^{abcdefghijklmnopqrs}	6.99^{QRS}	20.25^{JKLMNOPQR}	20.4^{pqrstuvwxyzABCDEF}
IITA686/LunT-387-301 (E40)	0.36^{ABCDE}	0.27^{jk}	1.33^{klmnop}	0.06^{z}	0.17^{xyzABC}	0.1k	0.37^{t}	100^{klmnopqrs}	8.26^{abcdefghijklmno}	7.25^{FGHIJKL}	45.63^{efghijklmno}	25.3^{bcdefghijklm}
IITA686/LunT-388-302 (E41)	0.44^{tuvwxyz}	0.4^{fg}	1.1^{CDEFGHI}	0.05^{A}	0.11^{DEFGHI}	0.1k	0.25^{y}	78^{BCDEFGHIJKL}	6.79^{bcdefghijklmnopqrstuvw}	7.48^{vwxy}	41.94^{nopqrs}	15.6^{IJKLMNOPQRSTUVWXY}

Continued

Genotype name (code)	SS (g)	SV (ml)	ρ (g ml⁻¹)	HC (ml g⁻¹)	HI	SC	SI	CT (mins)	EC (kΩ cm⁻¹)	pH	L*	Texture (N)
IITA686/LunT-390-304 (E42)	0.48^{pqrstuvw}	0.4^{fg}	1.2^{uvwxyzAB}	0.04^{B}	0.08^{GHIJKL}	0.03n	0.08^{IJ}	83^{wxyzABCDEFGH}	7.12^{abcdefghijklmnopqrstuvw}	7.26^{EFGHIJK}	14.64^{UVWX}	17.7^{BCDEFGHIJKLMNOPQR}
IITA686/LunT-398-310 (E43)	0.52^{mnopqrs}	0.4^{fg}	1.3^{lmnopqr}	0.04^{B}	0.08^{GHIJKL}	0.07L	0.18^{C}	100^{lmnopqrs}	8.48^{abcdefghijklmno}	6.53^{ghi1hi1ijk1l1}	21.28^{JKLMNO}	22.3^{hijklmnopqrstuvwxyz}
IITA686/LunT-403-314 (E44)	0.43^{uvwxyzA}	0.27^{jk}	1.59^{bc}	0.34^{e}	0.79^{bc}	0.43b	1.6a	51^{STUV}	5.38^{stuvw}	8.09^{ef}	58.45^{a}	7.7^{gh1i1j1k1}
IITA686/LunT-403-315 (E45)	0.52^{mnopqrs}	0.4^{fg}	1.3^{lmnopqr}	0.06^{z}	0.12^{CDEFGH}	0.1k	0.25^{y}	102^{jklmnopq}	8.31^{abcdefghijklmnopq}	6.47^{kl1lmn1o1}	43.75^{jklmnopqrs}	22.6^{ghijklmnopqrstuvwx}
IITA686/LunT-408-318 (E46)	0.56^{jklmno}	0.43^{ef}	1.3^{lmnopqr}	0.15^{q}	0.27^{opqrs}	0.17h	0.4^{s}	92^{pqrstuvwxyzA}	7.79^{abcdefghijklmnopqrst}	7.26^{EFGHIJK}	18.94^{IJKLMNOPQRSTUVW}	19.9^{qrstuvwxyzABCDEFGHI}
IITA686/LunT-415-321 (E47)	0.66^{def}	0.53^{cd}	1.26^{opqrstuv}	0.06^{z}	0.09^{FGHIJK}	0.1k	0.19^{BC}	88^{stuvwxyzABC}	7.42^{abcdefghijklmnopqrstu}	7.28^{DEFGHIJ}	19^{IJKLMNOPQRSTUVW}	19^{uvwxyzABCDEFGHIJKLMN}
IITA686/LunT-416-322 (E48)	0.35^{BCDE}	0.3^{ij}	1.17^{wxyzABCD}	0.09^{w}	0.26^{pqrst}	0.13i	0.43^{r}	111^{efghijkl}	8.71^{abcdefghijklmn}	6.39^{q1r1}	42.12^{nopqrs}	12.5^{UVWXYZa1b1c1d1e1}
IITA686/LunT-419-324 (E49)	0.75^{bc}	0.6^{b}	1.25^{pqrstuvw}	0.05^{A}	0.07^{HIJKLM}	0.07L	0.12^{G}	87^{stuvwxyzABCD}	7.42^{abcdefghijklmnopqrstu}	7.44^{wxyz}	17.23^{MNOPQRSTUVWX}	18.1^{yzABCDEFGHIJKLMNOPQR}
IITA686/LunT-420-325 (E50)	0.44^{uvwxyz}	0.33^{hij}	1.33^{klmnop}	0.01^{E}	0.02^{M}	0.02o	0.06^{KL}	69^{IJKLMNOPQ}	6.09^{hijklmnopqrstuvw}	7.95^{ghi}	14.63^{UVWX}	12.1^{VWXYZa1b1c1d1e1f1g1}
IITA686/LunT-423-328 (E51)	0.54^{klmnopq}	0.4^{fg}	1.35^{klmn}	0.04^{B}	0.07^{HIJKLM}	0.03n	0.08^{IJ}	99^{lmopqrst}	8.43^{abcdefghijklmno}	6.6^{d1e1f1g1h1l1}	17.58^{MNOPQRSTUVWX}	21.8$^{lmnopqrstuvwxyzAB C}$
IITA686/LunT-426-329 (E52)	0.54^{klmnopq}	0.37^{ghij}	1.46^{ghi}	0.08^{x}	0.15^{zABCDE}	0.2 g	0.54^{n}	72^{FGHIJKLMNOP}	6.35^{efghijklmnopqrstuvw}	7.8^{jklmno}	28.49^{ABCDE}	13.1^{STUVWXYZa1b1c1d1}
IITA686/LunT-427-330 (E53)	0.39^{xyzABCDE}	0.33^{hij}	1.18^{wxyzABC}	0.08^{x}	0.21^{tuvwxy}	0.07L	0.21^{A}	60^{OPQRST}	5.77^{nopqrstuvw}	8.05^{efg}	42.02^{nopqrs}	9.3^{d1e1f1g1h1i1j1k1}
IITA686/LunT-433-336 (E54)	0.45^{stuvwxyz}	0.37^{ghij}	1.22^{stuvwxyz}	0.06^{z}	0.13^{BCDEFG}	0.1k	0.27^{x}	83^{wxyzABCDEFGH}	7.07^{abcdefghijklmnopqrstuvw}	7.29^{CDEFGHI}	18.15^{KLMNOPQRSTUVWX}	17.9^{zABCDEFGHIJKLMNOPQR}
IITA686/LunT-444-346 (E55)	0.54^{klmnopq}	0.47^{de}	1.15^{yzABCDEF}	0.05^{A}	0.09^{FGHIJK}	0.03n	0.06^{KL}	92^{pqrstuvwxyzA}	7.78^{abcdefghijklmnopqrst}	6.68^{a1b1c1d1e1f1}	18.96^{JKLMNOPQRSTUVW}	19.9^{qrstuvwxyzABCDEFGHI}
KANO2 (E56)	0.48^{pqrstuvw}	0.37^{fgh}	1.3^{lmnopqr}	0.31^{f}	0.65 fg	0.3d	0.81g	68^{KLMNOPQR}	5.97^{jklmnopqrstuvw}	7.51^{uvw}	45.19^{hijklmnopq}	11.7^{XYZa1b1c1d1e1f1g1}
KENYA CAPSTONE (E57)	0.6^{ghijkl}	0.53^{cd}	1.13^{ABCDEFGH}	0.3^{g}	0.5^{i}	0.3^{d}	0.57^{m}	79^{ABCDEFGHIJK}	7.52^{abcdefghijklmnopqrstu}	7.39^{xyzABCD}	52.11^{bcd}	15.7^{HIJKLMNOPQRSTUVWX}
LUNT (E58)	0.52^{mnopqrs}	0.4^{fg}	1.3^{lmnopqr}	0.08^{x}	0.15^{ABCDE}	0.07^{l}	0.18^{C}	98^{lmnopqrstu}	8.19^{abcdefghijklmnopqr}	6.85^{UVWXY}	50.04^{defgh}	24.8^{cdefghijklmno}
MOQ-4 (E59)	0.54^{klmnopq}	0.47^{de}	1.15^{yzABCDEF}	0.05^{A}	0.09^{FGHIJK}	0.03^{n}	0.06^{KL}	120^{bcdef}	9.15^{abcdef}	5.58$^{×1y1}$	31.27^{wxyzABC}	27.1^{bcdef}
NAV 4 (E60)	0.34^{CDE}	0.27^{jk}	1.26^{opqrstuv}	0.3^{g}	0.88^{a}	0.3^{d}	1.11^{d}	44^{UV}	4.78^{uvw}	8.5^{b}	46.58^{efghijklmn}	6.1^{j1k1}
PONG-BR (E61)	0.56^{klmno}	0.43^{ef}	1.3^{lmnopqr}	0.05^{A}	0.09^{FGHIJK}	0.07^{l}	0.16^{D}	116^{cdefghi}	8.98^{abcdefgh}	6.26^{z1}	33.82^{wxyz}	26.5^{bcdefghi}
PONG-CR (E62)	0.58^{ghijklm}	0.43^{ef}	1.35^{jklmn}	0.26^{i}	0.45^{ijkl}	0.2^{g}	0.47q	76^{CDEFGHIJKL}	6.5^{cdefghijklmnopqrstuvw}	7.23^{FGHIJKLM}	43.25^{klmnopqrs}	14.6$^{NOPQRSTUVWXY Za1b1}$
S19 (E63)	0.4^{xyzABCD}	0.33^{hij}	1.21^{stuvwxyzA}	0.07^{y}	0.18^{wxyzAB}	0.07^{l}	0.21^{x}	95^{nopqrstuvwx}	7.93^{abcdefghijklmnopqrs}	6.77^{XYZa1b1}	22.51^{GHIJKL}	20.3^{pqrstuvwxyzABCDEFG}
S19/Ankpa4-100-87 (E64)	0.41^{wxyzABC}	0.33^{hij}	1.24^{qrstuvwx}	0.19^{m}	0.46^{ijk}	0.2^{g}	0.61^{l}	40^{V}	4.46^{w}	8.88^{a}	16.82^{MNOPQRSTUVWX}	5.4^{k1}
S19/Ankpa4-106-92 (E65)	0.33^{DE}	0.3^{ij}	1.1^{CDEFGHI}	0.21^{k}	0.64^{fg}	0.2^{g}	0.67^{j}	147^{a}	9.87^{a}	5.33^{A1}	41.46^{pqrs}	32.7a
S19/Ankpa4-108-93 (E66)	0.61^{fghijk}	0.47^{de}	1.3^{lmnopqr}	0.08^{x}	0.13^{BCDEFG}	0.03^{n}	0.06^{KL}	94^{nopqrstuvwy}	7.94^{abcdefghijklmnopqrs}	6.92^{STUV}	17.49^{MNOPQRSTUVWX}	20.7^{opqrstuvwxyzABCDE}
S19/Ankpa4-112-96 (E67)	0.25^{F}	0.23^{k}	1.09^{DEFGHI}	0.19^{m}	0.76^{cd}	0.2^{g}	0.87^{f}	72^{FGHIJKLMNOP}	6.41^{defghijklmnopqrstuvw}	7.49^{uvwx}	45.5^{hijklmnop}	12.6^{UVWXYZa1b1c1d1e1}
S19/Ankpa4-115-99 (E68)	0.52^{mnopqrs}	0.33^{hij}	1.56^{cde}	0.06^{z}	0.12^{CDEFGH}	0.1^{k}	0.3^{w}	80^{ABCDEFGHIJ}	6.95^{abcdefghijklmnopqrstu}	7.49^{uvwx}	18.57^{JKLMNOPQRSTUVWX}	16.1^{FGHIJKLMNOPQRSTUVWX}
S19/Ankpa4-12-11 (E69)	0.49^{opqrstuv}	0.33^{hij}	1.48^{efgh}	0.34^{e}	0.69^{ef}	0.12^{j}	0.36^{tu}	96^{nopqrstuvw}	7.91^{abcdefghijklmnopqrs}	6.79^{WXYZa1}	16.6^{OPQRSTUVWX}	23.9^{cdefghijklmnopqr}
S19/Ankpa4-122-104 (E70)	0.54^{klmnopq}	0.4^{fg}	1.35^{jklmn}	0.09^{w}	0.17^{xyzABC}	0.1^{k}	0.25^{y}	82^{xyzABCDEFGHI}	6.92^{bcdefghijklmnopqrstuvw}	7.15^{KLMNOP}	19.61^{IJKLMNOPQRST}	16.9^{DEFGHIJKLMNOPQRSTU}
S19/Ankpa4-124-106 (E71)	0.56^{jklmn}	0.43^{ef}	1.3^{lmnopqr}	0.11^{u}	0.2^{uvwxyz}	0.13^{i}	0.3^{x}	88^{stuvwxyzABC}	7.41^{abcdefghijklmnopqrst}	7.19^{JKLMNOP}	18.17^{KLMNOPQRSTUVWX}	20.7^{opqrstuvwxyzABCDE}
S19/Ankpa4-125-107 (E72)	0.46^{stuvwxy}	0.37^{fgh}	1.24^{qrstuvwx}	0.01^{E}	0.02^{M}	0.1^{k}	0.27^{x}	98^{lmnopqrstu}	8.18^{abcdefghijklmnopqr}	7.1^{NOPQ}	46.04^{fghijklmnop}	20.8^{nopqrstuvwxyzABCD}

Continued

Genotype name (code)	SS (g)	SV (ml)	ρ (g ml^{-1})	HC (ml g^{-1})	HI	SC	SI	CT (mins)	EC (kΩ cm^{-1})	pH	L*	Texture (N)
S19/Ankpa4-130-112 (E73)	0.61[fghijk]	0.33[hij]	1.85[a]	0.03[C]	0.05[IJKLM]	0.2[g]	0.61[l]	61[NOPQRST]	5.78[nopqrstuvw]	8.25[cd]	29.6[yzABCD]	9[d1e1f1g1h1i1j1k1]
S19/Ankpa4-13-12 (E74)	0.65[defg]	0.5[d]	1.3[lmnopqr]	0.12[t]	0.18[wxyzAB]	0.13[i]	0.26[xy]	75[CDEFGHIJKLM]	6.47[defghijklmnopqrstuvw]	7.74[lmnopq]	18.95[JKLMNOPQRSTUVW]	14.2[OPQRSTUVWXYZa1b1c1]
S19/Ankpa4-133-114 (E75)	0.34[CDE]	0.3[ij]	1.13[ABCDEFGH]	0.1[v]	0.29[opqr]	0.1[k]	0.33[v]	86[tuvwxyzABCDE]	7.49[abcdefghijklmnopqrstu]	7.17[JKLMNOP]	18.59[KLMNOPQRSTUVWX]	18.3[yzABCDEFGHIJKLMNOPQ]
S19/Ankpa4-136-116 (E76)	0.77[abc]	0.67[a]	1.15[yzABCDEF]	0.05[A]	0.06[IJKLM]	0.07[l]	0.1[H]	87[stuvwxyzABCD]	7.33[abcdefghijklmnopqrstuvw]	7.33[zABCDEF]	16.75[NOPQRSTUVWX]	18.5[wxyzABCDEFGHIJKLMNO]
S19/Ankpa4-137-117 (E77)	0.38[zABCDE]	0.3[ij]	1.27[nopqrstu]	0.07[y]	0.18[wxyzAB]	0.07[l]	0.23[z]	94[nopqrstuvwxy]	7.85[abcdefghijklmnopqrs]	6.9[STUVW]	19.02[JKLMNOPQRSTUVW]	20.3[pqrstuvwxyzABCDEFG]
S19/Ankpa4-139-119 (E78)	0.5[lmnopqrst]	0.5[d]	1.02[ll]	0.07[y]	0.14[ABCDEF]	0.02[o]	0.04[MN]	96[nopqrstuvw]	7.97[abcdefghijklmnopqrs]	6.59[ef1fg1h1i1j1]	17.6[MNOPQRSTUVWX]	20.7[opqrstuvwxyzABCDE]
S19/Ankpa4-141-121 (E79)	0.66[def]	0.53[cd]	1.25[pqrstuvw]	0.18[n]	0.27[opqrs]	0.23[f]	0.43[r]	55[RSTU]	5.42[qrstuvw]	8.03[efg]	17.76[LMNOPQRSTUVWX]	8[f1g1h1i1j1k1]
S19/Ankpa4-148-127 (E80)	0.56[ijklmno]	0.47[de]	1.19[uvwxyzAB]	0.06[z]	0.11[DEFGH]	0.02[o]	0.04[MN]	69[IJKLMNOPQ]	6.21[ghijklmnopqrstuvw]	8.11[e]	35.11[tuvw]	15.6[IJKLMNOPQRSTUVWXY]
S19/Ankpa4-158-134 (E81)	0.53[lmnopqr]	0.43[ef]	1.23[rstuvwxy]	0.13[s]	0.26[pqrst]	0.1[k]	0.23[z]	93[opqrstuvwxyz]	7.8[abcdefghijklmnopqrst]	6.99[QRS]	17.93[LMNOPQRSTUVWX]	20.1[pqrstuvwxyzABCDEFGH]
S19/Ankpa4-161-136 (E82)	0.57[hijklmn]	0.47[de]	1.21[stuvwxyzA]	0.03[C]	0.05[IJKLM]	0.02[o]	0.04[MN]	117[cdefgh]	9.11[abcdefg]	5.61[×1y1]	18.29[KLMNOPQRSTUVWX]	26.4[bcdefghijk]
S19/Ankpa4-171-143 (E83)	0.48[pqrstuvw]	0.43[ef]	1.12[BCDEFGH]	0.03[C]	0.06[IJKLM]	0.02[o]	0.05[LM]	125[bcd]	9.26[abcde]	5.5[y1z1]	14.65[UVWX]	28.3[abc]
S19/Ankpa4-17-16 (E84)	0.42[wxyzAB]	0.33[hij]	1.27[nopqrstu]	0.07[y]	0.17[xyzABC]	0.03[n]	0.09[HI]	105[ghijklmnop]	8.43[abcdefghijklmno]	6.25[r1]	19.16[IJKLMNOPQRSTUV]	23.7[defghijklmnopqrs]
S19/Ankpa4-176-147 (E85)	0.56[ijklmno]	0.47[de]	1.19[uvwxyzAB]	0.03[C]	0.05[IJKLM]	0.03[n]	0.06[KL]	100[klmnopqrs]	8.17[abcdefghijklmnopqr]	6.53[gh1i1j1k1l1]	16.51[OPQRSTUVWX]	22.6[ghijklmnopqrstuvwx]
S19/Ankpa4-179-150 (E86)	0.47[qrstuvwx]	0.37[fgh]	1.27[nopqrstu]	0.07[y]	0.15[zABCDE]	0.1[k]	0.27[x]	118[bcdefg]	9.03[abcdefg]	5.73[u1v1w1]	18.53[KLMNOPQRSTUVWX]	26.8[bcdefg]
S19/Ankpa4-18-17 (E87)	0.54[klmnopq]	0.3[ij]	1.8[a]	0.03[C]	0.06[IJKLM]	0.17[h]	0.57[m]	66[KLMNOPQR]	5.89[lmnopqrstuvw]	7.84[ijklm]	44.12[ijklmnopqrs]	11.8[WXYZa1b1c1d1e1f1g1]
S19/Ankpa4-182-153 (E88)	0.47[qrstuvwx]	0.4[fg]	1.18[wxyzABC]	0.04[B]	0.09[FGHIJK]	0.07[l]	0.18[C]	110[efghijklm]	8.65[abcdefghijklmn]	6.38[o1p1q1]	47.65[defghijkl]	25.2[bcdefghijklmn]
S19/Ankpa4-188-159 (E89)	0.46[stuvwxy]	0.43[ef]	1.07[FGHIJ]	0.01[E]	0.02[M]	0.03[n]	0.07[JK]	96[nopqrstuvw]	7.9[abcdefghijklmnopqrs]	6.74[YZa1b1c1]	42.74[mopqrs]	20.8[nopqrstuvwxyzABCD]
S19/Ankpa4-190-160 (E90)	0.5[nopqrstu]	0.43[ef]	1.16[xyzABCDE]	0.06[z]	0.12[CDEFGH]	0.02[o]	0.05[LM]	94[nopqrstuvwxy]	7.98[abcdefghijklmnopqrs]	6.93[STU]	19.51[IJKLMNOPQRSTU]	20.5[opqrstuvwxyzABCDEF]
S19/Ankpa4-192-162 (E91)	0.58[ghijklm]	0.4[fg]	1.45[ghi]	0.02[D]	0.03[LM]	0.07[l]	0.18[C]	77[CDEFGHIJKL]	6.61[cdefghijklmnopqrstuvw]	7.63[qrst]	16.66[OPQRSTUVWX]	14.9[LMNOPQRSTUVWXYZa1]
S19/Ankpa4-199-169 (E92)	0.75[bc]	0.63[ab]	1.19[uvwxyzAB]	0.07[y]	0.09[FGHIJK]	0.03[n]	0.05[LM]	101[jklmnopqr]	8.45[abcdefghijklmnopqrst]	6.6[d1e1f1g1h1i1]	41.23[pqrs]	22.5[ghijklmnopqrstuvwxy]
S19/Ankpa4-20-18 (E93)	0.67[def]	0.57[bc]	1.18[uvwxyzAB]	0.03[C]	0.04[KLM]	0.02[o]	0.04[MN]	97[mopqrstuv]	7.8[abcdefghijklmnopqrst]	6.81[VWXYZ]	14.26[WX]	20.3[pqrstuvwxyzABCDEFG]
S19/Ankpa4-206-175 (E94)	0.47[qrstuvwx]	0.33[hij]	1.42[ghij]	0.04[B]	0.09[FGHIJK]	0.03[n]	0.09[HI]	114[defghij]	8.87[abcdefghij]	5.74[u1v1]	48.13[defghij]	26.2[bcdefghijk]
S19/Ankpa4-210-178 (E95)	0.45[stuvwxyz]	0.33[hij]	1.36[jklm]	0.03[C]	0.07[HIJKLM]	0.07[l]	0.21[A]	87[stuvwxyzABCD]	7.21[abcdefghijklmnopqrstuvw]	7.4[wxyzABC]	28.62[ABCDE]	18.7[wxyzABCDEFGHIJKLMN]
S19/Ankpa4-21-19 (E96)	0.72[bcd]	0.63[ab]	1.14[zABCDEFG]	0.12[t]	0.17[xyzABC]	0.03[n]	0.05[LM]	104[hijklmnopq]	8.41[abcdefghijklmno]	6.32[q1r1]	16.96[MNOPQRSTUVWX]	23.9[defghijklmnopqr]
S19/Ankpa4-212-180 (E97)	0.54[klmnopq]	0.43[ef]	1.26[opqrstuv]	0.05[A]	0.09[FGHIJK]	0.02[o]	0.05[LM]	100[klmnopqrs]	8.21[abcdefghijklmnopqr]	6.58[f1g1h1i1j1k1]	17.22[MNOPQRSTUVWX]	22.3[hijklmnopqrstuvwxyz]
S19/Ankpa4-215-182 (E98)	0.61[fghijk]	0.53[cd]	1.15[yzABCDEF]	0.03[C]	0.05[IJKLM]	0.02[o]	0.04[MN]	74[DEFGHIJKLMN]	6.41[defghijklmnopqrstuvw]	7.7[nopqrs]	29.48[yzABCD]	13.9[QRSTUVWXYZa1b1c1]
S19/Ankpa4-219-185 (E99)	0.44[uvwxyz]	0.34[ghi]	1.29[lmnopqrs]	0.03[C]	0.07[HIJKLM]	0.02[o]	0.06[KL]	91[qrstuvwxyzAB]	7.7[abcdefghijklmnopqrstu]	7.11[NOP]	18.14[KLMNOPQRSTUVWX]	19.3[stuvwxyzABCDEFGHIJKL]
S19/Ankpa4-222-187 (E100)	0.44[uvwxyz]	0.33[hij]	1.33[klmnop]	0.06[z]	0.14[ABCDEF]	0.1[k]	0.3[w]	86[tuvwxyzABCDE]	7.3[abcdefghijklmnopqrstuvw]	7.21[GHIJKLMN]	20.35[IJKLMNOPQ]	26.1[bcdefghijk]
S19/Ankpa4-224-189 (E101)	0.58[ghijklm]	0.43[ef]	1.35[jklmn]	0.03[C]	0.05[IJKLM]	0.03[n]	0.07[JK]	107[fghijklm]	8.48[abcdefghijklmn]	6.63[×1d1e1f1g1h1]	19.4[IJKLMNOPQRSTUV]	24[cdefghijkl]
S19/Ankpa4-226-191 (E102)	0.63[fghi]	0.47[de]	1.34[jklmno]	0.02[D]	0.03[LM]	0.03[n]	0.06[KL]	86[tuvwxyzABCDE]	8.31[abcdefghijklmnopq]	7.29[CDEFGH]	16.69[NOPQRSTUVWX]	17.9[zABCDEFGHIJKLMNOPQR]
S19/Ankpa4-228-192 (E103)	0.6[fghijkl]	0.5[d]	1.2[tuvwxyzAB]	0.07[y]	0.12[CDEFGH]	0.1[k]	0.2[AB]	98[lmnopqrstu]	7.93[abcdefghijklmnopqrs]	6.71[Za1b1c1d1]	15.92[PQRSTUVWX]	20.8[nopqrstuvwxyzABCD]

Continued

Genotype name (code)	SS (g)	SV (ml)	ρ (g ml^{-1})	HC (ml g^{-1})	HI	SC	SI	CT (mins)	EC (kΩ cm^{-1})	pH	L*	Texture (N)
S19/Ankpa4-231-191 (E104)	$0.45^{stuvwxyz}$	0.33^{hij}	1.36^{jklm}	0.08^{x}	0.18^{wxyzAB}	0.07^{l}	0.21^{A}	$91^{qrstuvwxyzAB}$	$7.71^{abcdefghijklmnopqrst}$	7.14^{LMNOP}	$19.43^{IJKLMNOPQRSTUV}$	$19.6^{stuvwxyzABCDEFG HIJ}$
S19/Ankpa4-232-194 (E105)	0.62^{fghij}	0.53^{ef}	$1.17^{wxyzABCD}$	0.02^{D}	0.03^{LM}	0.07^{l}	0.13^{FG}	$80^{zABCDEFGHIJ}$	$7.04^{abcdefghijklmnopqrstuvw}$	7.43^{wxyzA}	$18.91^{IJKLMNOPQRSTUVW}$	$16.3^{EFGHIJKLMNOPQRSTUV}$
S19/Ankpa4-232-195 (E106)	$0.6^{fghijkl}$	0.4^{fg}	1.5^{defg}	0.05^{A}	0.08^{GHIJKL}	0.13^{i}	0.36^{tu}	$100^{klmnopqrs}$	$8.26^{abcdefghijklmnopqr}$	$6.49^{j1jlkllm1n1o1}$	$16.85^{MNOPQRSTUVWX}$	$22.2^{jklmnopqrstuvwxyzA}$
S19/Ankpa4-234-196 (E107)	0.62^{fghij}	0.4^{fg}	1.55^{cde}	0.19^{m}	0.31^{op}	0.3^{d}	0.75^{u}	$73^{EFGHIJKLMNO}$	$6.4^{defghijklmnopqrstuvw}$	7.69^{opqrs}	$43.43^{klmnopqrs}$	$13.2^{STUVWXYZa1b1c1d1}$
S19/Ankpa4-234-197 (E108)	$0.46^{stuvwxy}$	0.37^{fgh}	$1.24^{qrstuvwx}$	0.19^{m}	0.41^{klm}	0.13^{i}	0.35^{u}	55^{RSTU}	5.39^{stuvw}	7.85^{jkl}	34.35^{wxy}	$8.4^{e1f1g1h1i1j1k1}$
S19/Ankpa4-235-198 (E109)	$0.58^{ghijklm}$	0.53^{cd}	1.09^{DEFGHI}	0.02^{D}	0.03^{LM}	0.02^{o}	0.04^{MN}	$101^{klmnopqr}$	$8.36^{abcdefghijklmnop}$	$6.4^{n1o1p1q1}$	$47.41^{defghijklm}$	$22.6^{ghijklmnopqrstuvwx}$
S19/Ankpa4-238-201 (E110)	0.36^{ABCDE}	0.3^{ij}	$1.2^{tuvwxyzAB}$	0.07^{y}	0.19^{vwxyzA}	0.07^{l}	0.23^{z}	$72^{FGHIJKLMNOP}$	$7.34^{abcdefghijklmnopqrstuvw}$	7.73^{mnopq}	$16.23^{PQRSTUVWX}$	$12.8^{TUVWXYZa1b1c1d1e1}$
S19/Ankpa4-241-203 (E111)	$0.41^{wxyzABC}$	0.33^{hij}	$1.24^{qrstuvwx}$	0.15^{q}	0.37^{mn}	0.1^{k}	0.3^{w}	$84^{wxyzABCDEFG}$	$7.29^{abcdefghijklmnopqrstuvw}$	$7.24^{FGHIJKL}$	40.26^{rs}	$17.9^{zABCDEFGHIJKLMNOPQR}$
S19/Ankpa4-243-205 (E112)	$0.48^{pqrstuvw}$	0.37^{fgh}	$1.3^{lmnopqr}$	0.05^{A}	0.1^{EFGHIJ}	0.03^{n}	0.08^{JJ}	$105^{ghijklmnop}$	$6.99^{abcdefghijklmnopqrstuvw}$	6.35^{p1q1r1}	14.76^{TUVWX}	$23.4^{fghijklmnopqrstu}$
S19/Ankpa4-247-208 (E113)	0.39^{zABCDE}	0.37^{fgh}	1.05^{HIJ}	0.06^{z}	0.15^{zABCDE}	0.1^{k}	0.27^{x}	$101^{klmnopqr}$	$8.2^{abcdefghijklmnopqr}$	6.3^{q1r1}	$18.45^{IJKLMNOPQRSTUVWX}$	$22.1^{jklmnopqrstuvwxyzAB}$
S19/Ankpa4-249-210 (E114)	$0.51^{mnopqrst}$	0.43^{ef}	$1.12^{BCDEFGH}$	0.05^{A}	0.1^{EFGHIJ}	0.07^{l}	0.62^{l}	$78^{BCDEFGHIJKL}$	$6.71^{bcdefghijklmnopqrstuvw}$	$7.39^{yyzABCD}$	33.32^{wxyzA}	$15.3^{JKLMNOPQRSTUVWXYZ}$
S19/Ankpa4-253-213 (E115)	$0.53^{lmnopqr}$	0.4^{fg}	1.36^{jklm}	0.01^{E}	0.02^{M}	0.02^{o}	0.05^{LM}	$99^{lmnopqst}$	$8.13^{abcdefghijklmnopqrs}$	$6.58^{f1g1h1i1j1k1}$	$16.63^{OPQRSTUVWX}$	$21.2^{mnopqrstuvwxyzABCD}$
S19/Ankpa4-254-215 (E116)	$0.5^{nopqrstu}$	0.37^{fgh}	1.35^{jklmn}	0.15^{q}	0.3^{pq}	0.13^{i}	0.35^{u}	$94^{nopqrstuvwxy}$	$7.96^{abcdefghijklmnopqrs}$	$6.67^{b1c1d1e1f1}$	$42.94^{lmnopqrs}$	$20.8^{nopqrstuvwxyzABCD}$
S19/Ankpa4-26-22 (E117)	$0.49^{opqrstuv}$	0.43^{ef}	$1.14^{zABCDEFG}$	0.15^{q}	0.31^{op}	0.1^{k}	0.23^{z}	$97^{mnopqrstuv}$	$7.95^{abcdefghijklmnopqrs}$	6.86^{TUVWX}	27.16^{CDEFG}	$20.8^{nopqrstuvwxyzABCD}$
S19/Ankpa4-28-24 (E118)	$0.47^{qrstuvwx}$	0.4^{fg}	$1.18^{wxyzABC}$	0.05^{A}	0.11^{DEFGH}	0.03^{n}	0.08^{JJ}	$72^{FGHIJKLMNOP}$	$6.35^{efghijklmnopqrstuvw}$	7.75^{klmnop}	$47.5^{defghijklm}$	$13.8^{RSTUVWXYZa1b1c1}$
S19/Ankpa4-32-28 (E119)	$0.5^{nopqrstu}$	0.37^{fgh}	1.35^{klmn}	0.16^{p}	0.32^{no}	0.2^{g}	0.54^{n}	$69^{IJKLMNOPQ}$	$7.32^{abcdefghijklmnopqrstuvw}$	7.95^{ghi}	29.37^{zABCD}	$11.9^{VWXYZa1b1c1d1e1f1g1}$
S19/Ankpa4-339-266 (E120)	0.6^{ghijkl}	0.4^{fg}	1.5^{defg}	0.34^{e}	0.57^{h}	0.1^{k}	0.25^{y}	$101^{klmnopqr}$	$8.31^{abcdefghijklmnopq}$	$6.51^{i1j1k1l1m1n1}$	34.75^{uvwx}	$22.7^{fghijklmnopqrstuvwx}$
S19/Ankpa4-36-31 (E121)	$0.58^{ghijklm}$	0.43^{ef}	1.35^{jklmn}	0.14^{r}	0.24^{rstuv}	0.13^{i}	0.3^{w}	$88^{stuvwxyzABC}$	$7.39^{abcdefghijklmnopqrstuv}$	7.15^{KLMNOP}	14.93^{STUVWX}	$18.4^{xyzABCDEFGHIJKLMNOP}$
S19/Ankpa4-40-35 (E122)	0.56^{jklmno}	0.4^{fg}	1.4^{hijk}	0.04^{B}	0.07^{HIJKLM}	0.1^{k}	0.25^{y}	$107^{fghijklmn}$	$8.41^{abcdefghijklmno}$	$6.69^{a1b1c1d1e1f}$	32.97^{wxyzA}	26.8^{bcdefg}
S19/Ankpa4-42-36 (E123)	$0.46^{stuvwxy}$	0.37^{fgh}	$1.24^{qrstuvwx}$	0.1^{v}	0.22^{stuvwx}	0.1^{k}	0.27^{x}	$87^{stuvwxyzABCD}$	$7.38^{abcdefghijklmnopqrstuvw}$	$7.31^{BCDEFGH}$	$19.9^{IJKLMNOPQR}$	$18.5^{wxyzABCDEFGHIJKLMNO}$
S19/Ankpa4-44-38 (E124)	$0.47^{qrstuvwx}$	0.4^{fg}	$1.18^{wxyzABC}$	0.12^{t}	0.26^{pqrst}	0.1^{k}	0.25^{y}	$75^{CDEFGHIJKLM}$	$6.55^{cdefghijklmnopqrstuvw}$	7.79^{jklmno}	$17.79^{LMNOPQRSTUVWX}$	$14.7^{MNOPQRSTUVWXYZa1b1}$
S19/Ankpa4-47-40 (E125)	$0.53^{lmnopqr}$	0.4^{fg}	1.33^{klmnop}	0.08^{x}	0.15^{zABCDE}	0.1^{k}	0.25^{y}	$102^{klmnopq}$	$8.31^{abcdefghijklmnopq}$	6.32^{q1r1}	$18.64^{KLMNOPQRSTUVWX}$	$22.9^{ghijklmnopqrstuvw}$
S19/Ankpa4-48-41 (E126)	$0.53^{lmnopqr}$	0.4^{fg}	1.36^{jklm}	0.07^{y}	0.13^{BCDEFG}	0.03^{n}	0.08^{JJ}	$95^{nopqrstuvwx}$	$7.96^{abcdefghijklmnopqrs}$	6.89^{STUVW}	23.11^{FGHIJ}	$20.8^{nopqrstuvwxyzABCD}$
S19/Ankpa4-49-42 (E127)	0.34^{CDE}	0.3^{jj}	0.01^{K}	0.07^{y}	0.21^{tuvwxy}	0.07^{l}	0.23^{z}	$80^{zABCDEFGHIJ}$	$6.98^{abcdefghijklmnopqrstuvw}$	7.49^{uvwx}	34.67^{vwx}	$15.9^{GHIJKLMNOPQRSTUVWXY}$
S19/Ankpa4-50-43 (E128)	0.67^{def}	0.43^{ef}	1.56^{cde}	0.05^{A}	0.07^{HIJKLM}	0.13^{i}	0.3^{w}	$62^{MNOPQRS}$	$5.83^{mnopqrstuvw}$	8.13^{e}	14.54^{VWX}	$10.3^{b1c1d1e1f1g1h1i1j1}$
S19/Ankpa4-51-44 (E129)	$0.52^{mnopqrs}$	0.4^{fg}	$1.3^{lmnopqr}$	0.05^{A}	0.1^{EFGHIJ}	0.03^{n}	0.08^{JJ}	$113^{defghijk}$	$8.81^{abcdefghijk}$	5.81^{t1u1}	$32.03^{wxyzABC}$	$26.4^{bcdefghijk}$
S19/Ankpa4-5-4 (E130)	$0.47^{qrstuvwx}$	0.37^{fgh}	$1.27^{nopqrstu}$	0.06^{r}	0.13^{BCDEFG}	0.03^{n}	0.08^{JJ}	$76^{CDEFGHIJKL}$	$7.9^{abcdefghijklmnopqrs}$	7.6^{rstu}	$43.92^{jklmnopqrs}$	$14.7^{MNOPQRSTUVWXYZa1b1}$
S19/Ankpa4-57-49 (E131)	0.56^{jklmno}	0.4^{fg}	1.4^{hijk}	0.14^{r}	0.25^{qrstu}	0.13^{i}	0.36^{tu}	$80^{zABCDEFGHIJ}$	$7.04^{abcdefghijklmnopqrstuvw}$	7.12^{MNOP}	$16.82^{MNOPQRSTUVWX}$	$16.1^{FGHIJKLMNOPQRSTUVWX}$
S19/Ankpa4-60-51 (E132)	$0.45^{stuvwxyz}$	0.33^{hij}	1.36^{jklm}	0.04^{B}	0.09^{FGHIJK}	0.13^{i}	0.4^{s}	$66^{KLMNOPQR}$	$5.88^{mnopqrstuvw}$	7.81^{jklmn}	14.92^{STUVWX}	$11.1^{Za1b1c1d1e1f1g1h1}$
S19/Ankpa4-61-52 (E133)	$0.43^{uvwwxyzA}$	0.37^{fgh}	$1.16^{xyzABCDE}$	0.03^{C}	0.07^{HIJKLM}	0.07^{l}	0.19^{BC}	$94^{nopqrstuvwy}$	$7.82^{abcdefghijklmnopqrs}$	$6.7^{za1b1c1d1e1}$	$17.15^{MNOPQRSTUVWX}$	$20.3^{pqrstuvwxyzABCDEFG}$
S19/Ankpa4-64-55 (E134)	0.56^{jklmno}	0.43^{ef}	$1.3^{lmnopqr}$	0.11^{u}	0.2^{uvwxyz}	0.13^{i}	0.3^{w}	$91^{qrstuvwxyzAB}$	$7.72^{abcdefghijklmnopqrst}$	$7.31^{BCDEFGH}$	$17^{MNOPQRSTUVWX}$	$19.1^{tuvwxyzABCDEFGHIJKLM}$

Continued

Genotype name (code)	SS (g)	SV (ml)	ρ (g ml⁻¹)	HC (ml g⁻¹)	HI	SC	SI	CT (mins)	EC (kΩ cm⁻¹)	pH	L*	Texture (N)
S19/Ankpa4-65-56 (E135)	0.79^ab	0.6^b	1.32^jklmnopq	0.08^x	0.1^EFGHIJ	0.07^l	0.12^G	101^jklmnopqr	8.29^abcdefghijklmnopqr	6.41^m1n1o1p1q1	16.14^PQRSTUVWX	22.9^ghijklmnopqrstuvw
S19/Ankpa4-67-58 (E136)	0.55^jklmnop	0.33^hij	1.67^b	0.07^y	0.13^BCDEFG	0.17^h	0.52^o	92^pqrstuvwxyzA	8.54^defghijklmno	6.91^STUV	27.96^BCDEF	19.99^qrstuvwxyzABCDEFGHI
S19/Ankpa4-69-60 (E137)	0.54^klmnopq	0.43^ef	1.26^b	0.11^u	0.2^uvwxyz	0.1^k	0.23^z	75^CDEFGHIJKLM	6.46^cdefghijklmnopqrstuvw	7.71^nopqr	46.79^efghijklmn	14.1^OPQRSTUVWXYZa1b1c1
S19/Ankpa4-72-63 (E138)	0.6^fghijkl	0.53^cd	1.13^ABCDEFGH	0.16^p	0.23^stuvw	0.1^k	0.19^BC	80^ABCDEFGHIJ	6.97^abcdefghijklmnopqrstuvw	7.41^wxyzAB	32.26^wxyzAB	16.3^EFGHIJKLMNOPQRSTUV
S19/Ankpa4-73-64 (E139)	0.55^jklmnop	0.5^d	1.1^CDEFGHI	0.01^E	0.02^M	0.03^n	0.06^KL	83^wxyzABCDEFGH	7.17^abcdefghijklmnopqrstuvw	7.21^GHIJKLMN	46.51^efghijklmn	17.2^DEFGHIJKLMNOPQRST
S19/Ankpa4-84-72 (E140)	0.48^pqrstuvw	0.4^fg	1.2^tuvwxyzAB	0.14^r	0.29^opqr	0.13^j	0.36^tu	70^HIJKLMNOP	6.37^abcdefghijklmnopqrs	7.84^ijklm	29.42^ABCD	12.4^VWXYZa1b1c1d1e1f1
S19/Ankpa4-86-74 (E141)	0.35^BCDE	0.33^hij	1.06^GHIJ	0.04^B	0.11^DEFGHI	0.07^l	0.21^A	93^opqrstuvwxyz	7.83^abcdefghijklmnopqrs	6.53^ghi1ij1k1l1	19.05^IJKLMNOPQRSTUVW	20.1^pqrstuvwxyzABCDEFGH
S19/Ankpa4-8-7 (E142)	0.4^xyzABCD	0.33^hij	1.21^stuvwxyzA	0.06^z	0.15^ABCDE	0.03^o	0.09^HI	85^uvwxyzABCDEF	6.22^defghijklmnopqrstuvw	7.29^CDEFGHI	19.4^IJKLMNOPQRSTUV	17.8^ABCDEFGHIJKLMNOPQR
S19/Ankpa4-88-75 (E143)	0.47^qrstuvwx	0.37^fgh	1.27^nopqrstu	0.06^z	0.13^BCDEFG	0.1^k	0.27^x	74^DEFGHIJKLMN	6.45^cdefghijklmnopqrstuvw	7.79^jklmno	18.98^IJKLMNOPQRSTUVW	14^PQRSTUVWXYZa1b1c1
S19/Ankpa4-88-76 (E144)	0.4^xyzABCD	0.33^klmnop	1.33^klmnop	0.06^z	0.15^ABCDE	0.02^o	0.06^KL	99^lmnopqrst	8.18^abcdefghijklmnopqr	6.52^h1i1j1k1l1m1	50.85^bcdef	20.9^mnopqrstuvwxyzABCD
S19/Ankpa4-89-102 (E145)	0.36^ABCDE	0.3^ij	1.2^tuvwxyzAB	0.16^p	0.44^jkl	0.17^h	0.57^m	74^DEFGHIJKLMN	6.62^cdefghijklmnopqrstuvw	7.32^ABCDEFG	45.92^ghijklmnop	14^PQRSTUVWXYZa1b1c1
S19/Ankpa4-89-76 (E146)	0.53^lmnopqr	0.43^ef	1.23^stuvwxy	0.06^z	0.11^DEFGHI	0.05^m	0.12^G	128^bc	9.35^abc	5.58^x1y1	20.01^IJKLMNOPQR	28.3^abc
S19/Ankpa4-90-77 (E147)	0.60^ghijkl	0.47^de	1.28^mopqrst	0.04^B	0.07^HIJKLM	0.03^n	0.06^KL	105^ghijklmnop	8.48^abcdefghijklmno	6.77^XYZa1b1	20.31^IJKLMNOPQR	24.2^cdefghijklmno
S19/Ankpa4-92-79 (E148)	0.55^klmnop	0.47^de	1.17^wxyzABCD	0.39^b	0.71^de	0.37^c	0.79^h	48^TUV	4.89^tuvw	8.34^c	55.49^ab	6.9^h1i1j1k1
S19/Ankpa4-93-80 (E149)	0.52^mnopqrs	0.4^fg	1.3^lmnopqr	0.06^z	0.12^CDEFGH	0.1^k	0.25^y	96^nopqrstuvw	7.96^abcdefghijklmnopqrs	6.64^c1d1e1f1g1	20.81^IJKLMNOP	20.2^pqrstuvwxyzABCDEFG
S19/Ankpa4-94-81 (E150)	0.66^def	0.5^d	1.32^klmnopq	0.06^z	0.09^FGHIJK	0.1^k	0.2^AB	84^wxyzABCDEFG	7.34^abcdefghijklmnopqrstuvw	7.2^HIJKLMNO	45.99^fghijklmnop	17.5^CDEFGHIJKLMNOPQRS
S19/Ankpa4-96-83 (E151)	0.62^ghij	0.47^de	1.32^klmnopq	0.06^z	0.1^EFGHIJ	0.1^k	0.21^A	91^qrstuvwxyzAB	7.75^abcdefghijklmnopqrst	6.97^RST	15.44^RSTUVWX	19.6^rstuvwxyzABCDEFGHIJ
S19/Ankpa4-96-84 (E152)	0.36^ABCDE	0.27^jk	1.33^klmnop	0.04^B	0.11^DEFGHI	0.07^l	0.26^xy	97^mnopqrstuv	8.02^abcdefghijklmnopqrs	6.45^l1m1n1o1p1	18.73^JKLMNOPQRSTUVWX	20.1^pqrstuvwxyzABCDEFGH
SONGKHLA (E153)	0.58^ghijklm	0.5^d	1.16^xyzABCDE	0.06^z	0.1^EFGHIJ	0.03^n	0.06^KL	131^b	9.55^ab	5.39^z1A1	26.3^DEFGH	29.5^ab
TIGID (E154)	0.43^uvwwxyzA	0.33^hij	1.3^lmnopqr	0.37^d	0.86^a	0.43^b	1.3^c	49^STUV	5.23^stuvw	8.34^c	55.34^abc	6.5^i1j1k1
UKZN-1 (E155)	0.47^rstuvwx	0.4^fg	1.18^wxyzABC	0.1^v	0.21^tuvwxy	0.1^k	0.25^y	106^ghijklmno	8.43^abcdefghijklmno	6.4^n1o1p1q1	54.99^abc	23.9^cdefghijklmnopqr
UNISWA (E156)	0.83^a	0.67^a	1.24^qrstuvwx	0.06^z	0.07^HIJKLM	0.02^o	0.03^N	126^bcd	9.28^abcd	5.42^z1A1	23.82^EFGHI	28.3^abc
l.s.d	0.033	0.029	0.035	0.003	0.023	0.003	0.006	6.001	1.267	0.048	2.117	1.928
cv%	9.900	29.900	12.800	8.200	14.700	23.600	20.900	5.400	8.200	16.400	27.300	11.800
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 2. Means for seed properties across 156 Bambara groundnut accessions. Different upper–case alpha–numeric within a column indicate significant differences among genotypes. SS: seed size; SV seed volume; ρ density; HC hydration capacity; SC swelling capacity; SI swelling index; CT cooking time; EC electrical conductivity; pH potential of hydrogen; L* lightness from black to white on a scale of zero to 100.
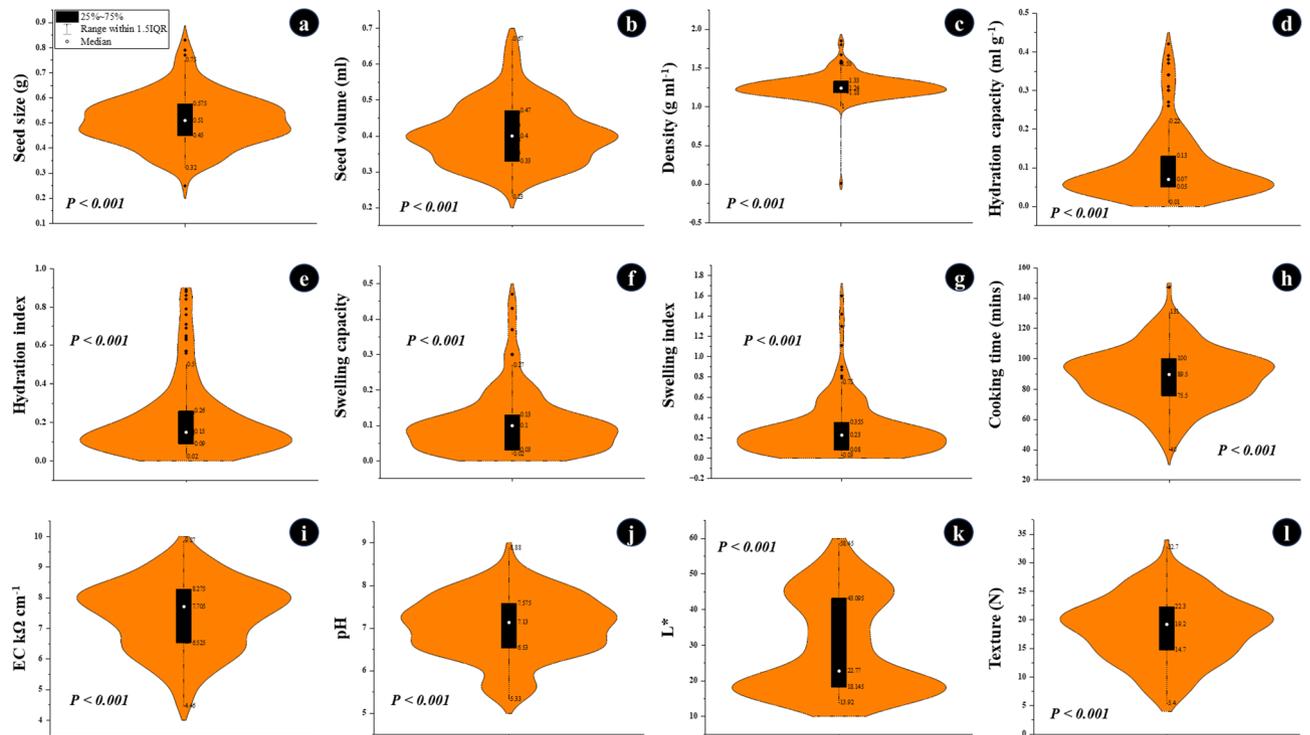
Fig. 3. Data visualisation with violin plots combining box plots and kernel density plots to represent the distribution and shape of recorded data among 156 Bambara groundnut accessions.

implies heterogeneity within the dataset and may necessitate separate analyses or modelling approaches for each subgroup. Texture data (Fig. 3k) is depicted using a constricted violin plot, indicating narrow data distribution and low variability.

Principal component analysis (PCA)

Table 3 shows the PCA with factor loadings, eigenvalues, and percent variance for the evaluated physicochemical traits. PC1 accounted for 44.187% of the total variation and was positively correlated with HC, SC, SI and pH. PC2 accounted for 18.437% of the total variation and was positively correlated with CT, EC, L*, a*, b* and texture. Seed size and SV were positively correlated with PC3, accounting for 12.158% of the total variation.

Based on the evaluated physicochemical properties, the PC biplots based on PCA analysis were used to picture the relationship among Bambara groundnut genotypes (Fig. 4). Traits depicted by parallel vectors or those positioned closely to each other indicate a strong positive association, whereas traits situated nearly opposite each other (at 180 °) demonstrate a highly negative association. Vectors directed towards the sides indicate a weaker relationship. BURKINA, IITA686/LunT-403-314, NAV4, S19/Ankpa4-92-79, TIGD, ANKPA 4, IITA686/LunT-261-220, IITA686/LunT-427-330 and KENYA CAPSTONE are grouped based on high HI, HC, SI and SC.

The genotypes IITA686/LunT-387-301, S19/Ankpa4-254-215, IITA686/LunT-305-243, S19/Ankpa4-5-4, S19/Ankpa4-339-266, S19/Ankpa4-49-42, and IITA686/LunT-360-280 are clustered together due to their high values of a*, b*, and L* parameters. This grouping suggests a similarity in lightness attributes among these genotypes, indicating potential common traits or characteristics in their colour profiles (Fig. 4).

The genotypes UNISWA, GHC37105, KANO2, S19/Ankpa4-89-76, S19/Ankpa4-171-143, S19/Ankpa4-161-136, S19/Ankpa4-179-150, and IITA686/LunT-334-262 have been clustered together due to their shared characteristics of high cooking time, electrical conductivity, and texture (Fig. 4).

S19/Ankpa4-17-16, IITA686/LunT-284-230, IITA686/LunT-366-285, IITA686/LunT-295-235, IITA686/LunT-415-321, IITA686/LunT-390-304, S19/Ankpa4-224-189, IITA686/LunT-419-324, S19/Ankpa4-232-195, IITA686/LunT-398-310, S19/Ankpa4-65-56, S19/Ankpa4-21-19, S19/Ankpa4-86-74, S19/Ankpa4-47-40 and S19/Ankpa4-247-208 are grouped based on high SS and SV (Fig. 4).

IITA686/LunT-337-264, IITA686/LunT-362-281, S19/Ankpa4-100-87, S19/Ankpa4-141-121, S19/Ankpa4-50-43, IITA686/LunT-420-325, IITA686/LunT-332-260, S19/Ankpa4-13-12, S19/Ankpa4-238-201, S19/Ankpa4-133-114, DodR, S19/Ankpa4-12-11 and IITA686/LunT-426-329 are grouped on high ρ and pH.

Pearson correlation analysis

Pearson correlation coefficients showing relationships among physicochemical traits evaluated among Bambara groundnut genotypes are presented in (Fig. 5a). Significant and positive correlations were observed between SS and SV ($r = 0.88$; $p = 0.028$). Seed hydration capacity was positively correlated with HI ($r = 0.94$; $p = 0.028$),

Traits	PC1	PC2	PC3
SS	-0.150	-0.118	0.669
SV	-0.181	-0.068	0.597
ρ	0.054	-0.100	0.190
HC	0.302	0.077	0.268
HI	0.323	0.096	0.083
SC	0.339	0.028	0.246
SI	0.349	0.050	0.098
CT	-0.334	0.259	0.030
EC	-0.331	0.253	0.028
pH	0.314	-0.269	-0.042
L*	0.192	0.488	0.032
a*	0.095	0.449	0.067
b*	0.176	0.508	0.034
Texture	-0.336	0.229	0.039
Eigenvalue	6.186	2.581	1.702
Variance (%)	44.187	18.437	12.158
Cumulative (%)	44.187	62.624	74.782

Table 3. Summary of factor loadings, eigenvalues, and percent variation for cooking quality parameters assessed for 156 Bambara groundnut genotypes. *SS* seed size; *SV* seed volume; *ρ* density; *HC* hydration capacity; *SC* swelling capacity; *SI* swelling index; *CT* cooking time; *EC* electrical conductivity; *pH* potential of hydrogen; *L** lightness from black to white on a scale of zero to 100.
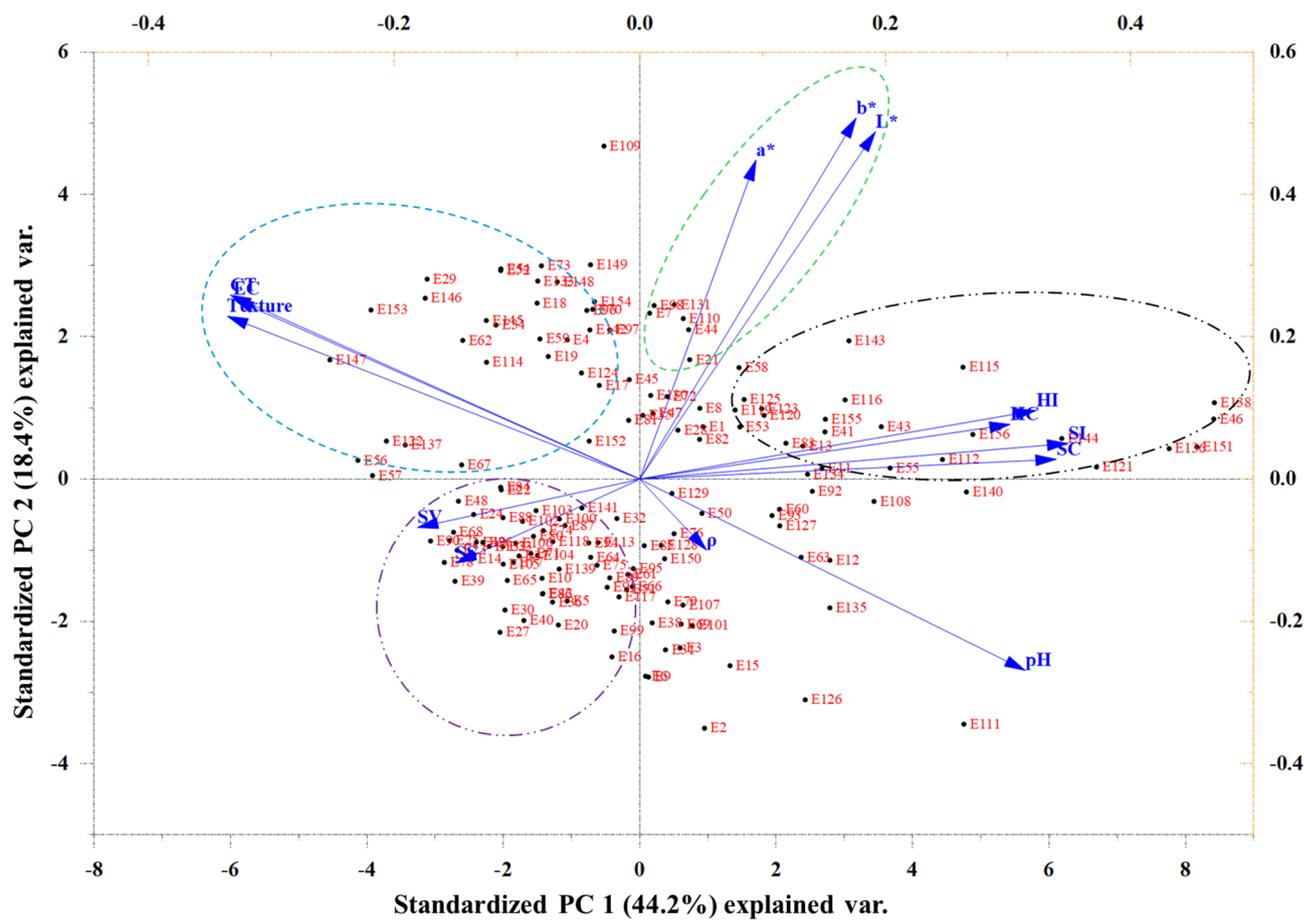
Fig. 4. Principal component (PC) biplot of PC 1 vs. PC 2 demonstrating the relationships among physicochemical properties among 156 Bambara groundnut genotypes.
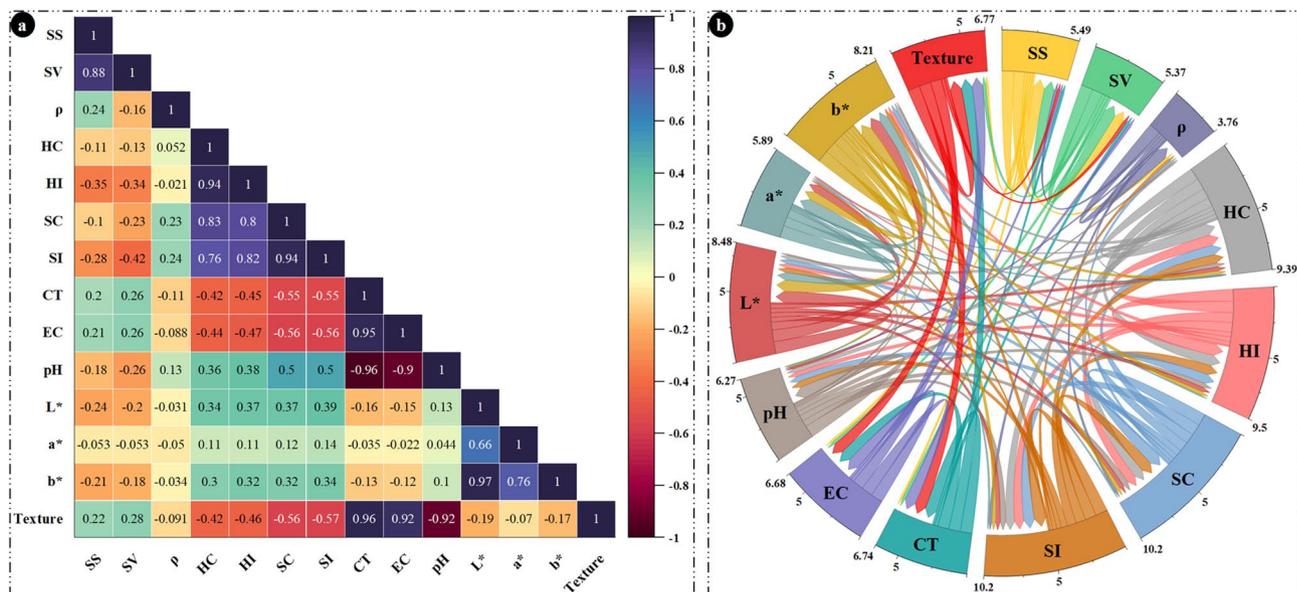
Fig. 5. Pairwise correlation matrix and chord diagram illustrating the relationships among evaluated BGN seed physicochemical properties: (**a**) heatmap of Pearson correlation coefficients between size (SS), seed volume (SV), density (ρ), hydration capacity (HC), swelling capacity (SC), swelling index (SI), cooking time (CT), electrical conductivity (EC), potential of hydrogen (pH), lightness from black to white on a scale of zero to 100 (L*), chromaticity with no specific numeric limits (a* and b*) and (**b**) circular chord diagram visualizing the strength and direction of relationships among traits. Thicker ribbons indicate stronger correlations, with the width and colour of the connections highlighting the degree of association.

SC ($r = 0.83$; $p = 0.035$) and SI ($r = 0.76$; $p = 0.037$). Cooking time was positively correlated with texture ($r = 0.96$; $p = 0.040$) and EC ($r = 0.95$; $p = <0.05$).

Significant and negative correlations were observed between SC and CT ($r = -0.55$; $p = 0.046$), EC ($r = -0.56$; $p = 0.041$) and texture ($r = -0.56$; $p = 0.039$). Significant inverse associations were also noted between pH and CT ($r = -0.96$; $p < 0.05$), EC ($r = -0.90$; $p = 0.010$) and texture ($r = -0.92$; $p = 0.037$) (Fig. 5a).

The circular chord diagram (Fig. 5b) illustrates the interrelationships among Bambara groundnut's various physicochemical, hydration, and cooking quality traits, with each segment around the circle representing a specific trait. The coloured ribbons, or chords, connecting these segments denote the degree of association between the traits—where thicker chords suggest stronger correlations and thinner ones indicate weaker associations.

Figure 5b reflects BGN's complex phenotypic integration among hydration, physical, and cooking-related traits. These insights are valuable for breeding programs, highlighting key trait combinations that can be targeted to develop fast-cooking, nutritionally rich, and consumer-acceptable BGN varieties. By visualizing these relationships, the chord diagram facilitates a holistic understanding of how different seed characteristics influence cooking quality, enabling more informed and efficient selection in breeding pipelines.

Agglomerative hierarchical clustering (AHC)

Based on cooking time and texture, BGN genotypes were clustered into five groups (Fig. 6). Group A (soft-cooking genotypes) comprised of 14 genotypes including DodR, BURKINA, ANKPA 4, TIGD, NAV 4, S19/Ankpa4-100-87 and IITA686/LunT-292-233. Group B (slightly soft-cooking genotypes) consisted of 27 genotypes, among which were PONG-CR, IITA686/LunT-420-325, S19/Ankpa4-89-102, KANO2, S19/Ankpa4-238-201, IITA686/LunT-314-249, IITA686/LunT-261-220, and S19/Ankpa4-5-4.

Group C (slightly hard-cooking genotypes) comprised of 37 genotypes including IITA686, S19/Ankpa4-122-104, S19/Ankpa4-73-64, S19/Ankpa4-241-203, IITA686/LunT-415-321, IITA686/LunT-419-324 and IITA686/LunT-262-221. Group D (moderately hard-cooking genotypes) comprised of 61 genotypes including S19/Ankpa4-61-52, S19/Ankpa4-190-160, S19/Ankpa4-108-93, UKZN-1, LUNT, S19, IITA686/LunT-444-346, IITA686/LunT-365-284 and IITA686/LunT-284-230. Group E (hard-cooking genotypes) comprised of 17 genotypes including DIP-C, MOQ-4, GHC37105, PONG-BR, SONGKHLA, UNISWA, S19/Ankpa4-206-175 and IITA686/LunT-334-262 (Fig. 6).

Proximate and mineral nutrient compositions

The proximate composition of raw and cooked BGN is shown in Tables 4 and 5. The results show that the concentrations of all proximate nutrients analysed were significantly different using a paired t-test. The protein content of raw BGN seeds ranged from 15.16 to 29.32 g/100 g^{-1}. The mean protein content of cooked BGN samples was significantly higher ($p = 0.035$) than the raw samples. The genotype DodR showed the highest protein recovery after cooking (19.09–25.39 g/100 g^{-1}). The fat content of raw BGN samples (3.16–5.55 g/100
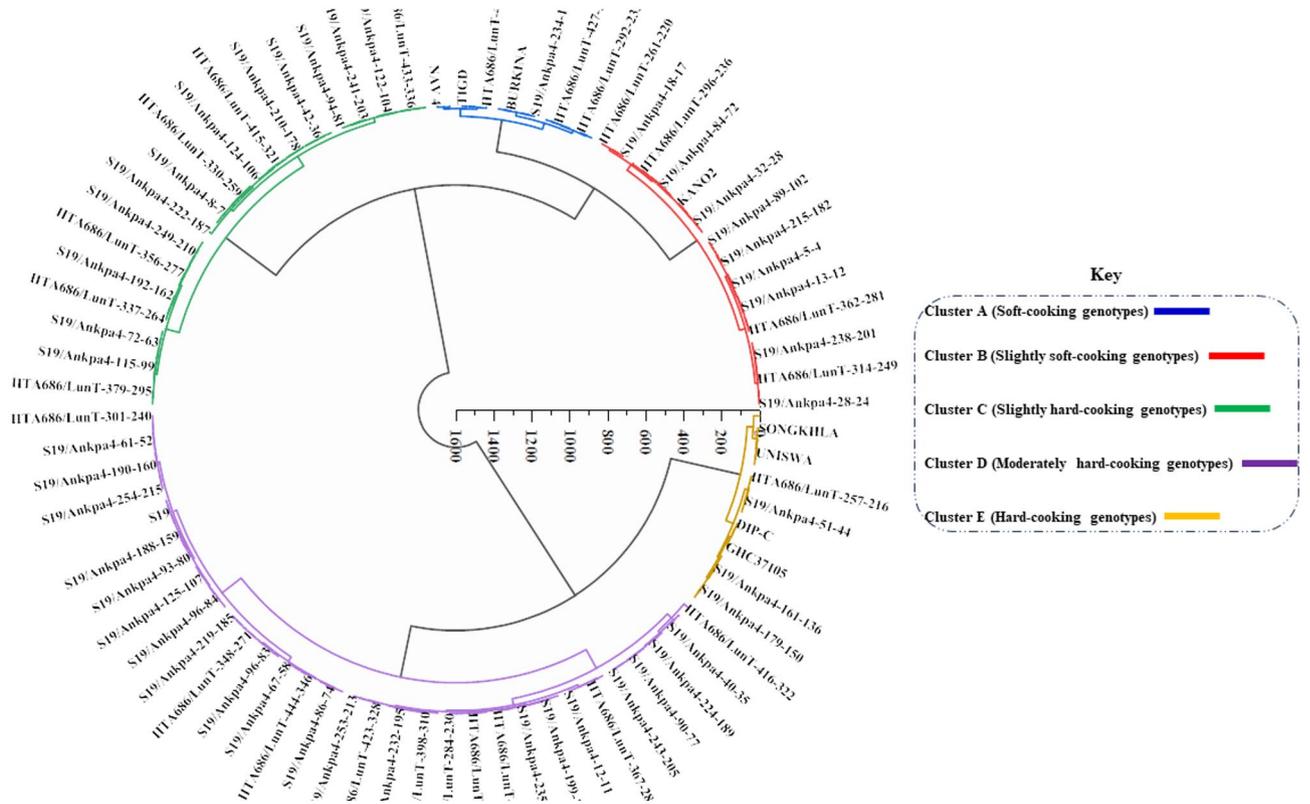
Fig. 6. Dendrogram showing agglomerative hierarchical clustering of 156 Bambara groundnut genotypes cooking quality.

Category	Genotype	Proximate composition					Macro-nutrients (g 100 g^{-1} DW)				Micro-nutrients (g 100 g^{-1} DW)				
		Protein	Fat	NDF	Ash	Moisture	P	K	Ca	Mg	Mn	Cu	Zn	Fe	Na
Fast cooking genotypes	S19/Ankpa4-100-87	22.410	3.900	40.560	4.860	8.040	0.044	0.159	0.005	0.015	0.900	1.200	2.400	2.600	0.001
	NAV 4	24.630	3.160	44.800	4.860	6.820	0.051	0.154	0.006	0.018	0.900	1.000	2.600	2.100	0.001
	S19/Ankpa4-92-79	28.560	3.830	36.180	5.100	7.590	0.059	0.16	0.009	0.019	0.600	1.500	2.800	1.700	0.002
	TIGD	28.580	3.210	38.730	4.180	6.520	0.044	0.17	0.009	0.023	1.300	0.600	2.600	2.100	0.001
	IITA686/LunT-403-314	25.820	4.140	36.420	4.570	6.660	0.043	0.147	0.007	0.017	0.900	0.700	2.600	2.400	0.001
	S19/Ankpa4-234-197	22.400	4.960	41.450	4.350	8.300	0.044	0.151	0.006	0.018	0.900	0.800	2.400	2.400	0.001
	S19/Ankpa4-141-121	23.740	3.720	28.290	4.670	8.260	0.045	0.154	0.004	0.016	0.900	0.900	2.400	2.600	0.001
	BURKINA	29.320	3.810	31.880	5.150	6.850	0.059	0.146	0.001	0.022	0.900	1.100	2.600	3.000	0.001
	ANKPA 4	25.330	3.950	34.950	5.230	7.900	0.051	0.176	0.005	0.015	1.100	0.900	2.600	2.800	0.001
	DodR	21.030	5.180	34.220	4.860	7.580	0.037	0.174	0.004	0.018	0.900	1.000	2.600	2.800	0.001
Slow cooking genotypes	S19/Ankpa4-106-92	25.270	4.380	20.950	4.810	8.310	0.057	0.159	0.006	0.019	1.100	1.200	3.000	2.800	0.001
	SONGKHLA	23.810	5.550	29.600	4.620	3.650	0.045	0.158	0.005	0.016	1.100	2.100	3.200	3.000	0.001
	S19/Ankpa4-89-76	22.000	4.360	20.070	4.980	7.260	0.042	0.167	0.005	0.018	0.900	0.800	2.600	4.300	0.001
	UNISWA	20.590	5.210	23.410	4.580	7.380	0.038	0.15	0.005	0.017	0.900	0.700	2.600	4.600	0.001
	S19/Ankpa4-171-143	24.950	3.950	28.130	4.900	7.730	0.042	0.169	0.004	0.017	1.100	0.800	2.400	2.600	0
	GHC37105	22.480	4.300	28.820	4.540	7.960	0.044	0.152	0.005	0.017	0.900	0.800	2.400	3.000	0.001
	DIP-C	18.820	5.520	27.680	4.250	8.450	0.037	0.138	0.007	0.017	0.900	0.700	2.600	2.400	0
	MOQ-4	15.160	4.490	28.370	4.470	7.730	0.038	0.159	0.004	0.017	1.100	0.600	2.400	3.000	0.001
	S19/Ankpa4-179-150	19.090	4.670	22.450	4.410	7.690	0.034	0.164	0.005	0.016	1.300	0.800	2.600	9.600	0
	IITA686/LunT-334-262	24.950	4.940	16.780	4.910	7.990	0.048	0.173	0.006	0.018	1.100	0.800	2.500	2.600	0.002

Table 4. Proximate, macro and micro-nutrient composition of 10 Bambara groundnut genotypes analysed in their Raw state, categorised as fastest and slowest cooking. *Protein (g 100 g^{-1} DW), Fat (g 100 g^{-1} DW), NDF (g 100 g^{-1} DW), Ash (g 100 g^{-1} DW) Moisture (%). *DW, Dry weight basis; NDF, Neutral detergent fibre.

Category	Genotype	Proximate composition					Macro-nutrients (g 100 g⁻¹ DW)				Micro-nutrients (g 100 g⁻¹ DW)				
		Protein	Fat	NDF	Ash	Moisture	P	K	Ca	Mg	Mn	Cu	Zn	Fe	Na
Fast cooking genotypes	S19/Ankpa4-100-87	24.950	5.950	16.780	4.850	3.650	0.048	0.122	0.012	0.017	1.000	1.100	2.500	2.900	0.002
	NAV 4	25.120	6.770	18.340	3.570	3.620	0.049	0.115	0.013	0.017	0.600	0.900	2.900	0.000	0.002
	S19/Ankpa4-92-79	25.950	6.420	49.250	4.330	1.820	0.046	0.073	0.012	0.018	0.400	2.000	2.600	0.000	0.002
	TIGD	27.850	6.740	16.680	2.980	3.360	0.056	0.093	0.018	0.023	0.600	3.100	2.900	0.000	0.002
	IITA686/LunT-403-314	25.820	6.890	56.710	3.280	3.860	0.047	0.046	0.017	0.015	0.600	2.100	2.500	0.000	0.002
	S19/Ankpa4-234-197	21.940	6.890	15.470	3.520	2.730	0.038	0.051	0.010	0.017	0.400	1.100	2.500	0.000	0.002
	S19/Ankpa4-141-121	24.530	6.580	58.320	3.370	2.310	0.044	0.095	0.009	0.015	0.400	1.500	2.500	0.000	0.002
	BURKINA	28.940	6.640	54.750	3.330	3.430	0.044	0.094	0.017	0.021	0.400	1.300	2.500	0.000	0.002
	ANKPA 4	27.240	6.180	20.050	3.460	3.470	0.046	0.053	0.011	0.014	0.600	1.500	2.700	0.000	0.002
	DodR	22.540	7.480	14.230	3.460	2.620	0.046	0.078	0.008	0.015	0.800	1.000	2.900	1.800	0.003
	S19/Ankpa4-106-92	27.090	6.390	55.980	3.780	2.700	0.036	0.100	0.013	0.018	1.300	1.400	3.300	2.500	0.003
	SONGKHLA	22.110	7.570	57.330	3.990	3.160	0.049	0.060	0.014	0.018	1.000	3.200	3.500	2.300	0.003
	S19/Ankpa4-89-76	24.430	6.930	58.650	3.590	4.340	0.042	0.114	0.015	0.017	1.000	2.400	3.100	1.600	0.007
	UNISWA	20.700	6.820	61.620	4.550	2.290	0.044	0.075	0.013	0.018	1.000	6.300	3.700	1.400	0.004
Slow cooking genotypes	S19/Ankpa4-171-143	25.670	6.320	56.580	3.290	2.200	0.037	0.149	0.015	0.016	1.200	1.600	2.900	1.900	0.006
	GHC37105	23.360	6.300	54.430	4.290	2.600	0.040	0.076	0.012	0.018	0.800	2.800	2.900	1.900	0.004
	DIP-C	24.000	8.160	17.310	3.070	3.860	0.042	0.126	0.011	0.016	0.800	1.700	3.100	1.400	0.005
	MOQ-4	18.230	7.300	64.090	3.400	3.150	0.039	0.075	0.011	0.014	0.800	1.700	2.700	1.400	0.002
	S19/Ankpa4-179-150	25.390	7.020	59.450	2.500	2.570	0.035	0.082	0.014	0.015	1.200	1.300	2.900	2.300	0.003
	IITA686/LunT-334-262	24.830	6.480	60.860	3.330	2.390	0.034	0.050	0.010	0.015	1.000	1.300	2.900	1.700	0.002
	Standard deviation	2.140	0.550	26.110	0.560	1.380	0.009	0.030	0.002	0.001	0.250	1.280	0.280	1.590	0.002
	t-value	−2.28*	−19.770**	−2.170*	0.890**	14.360**	1.040ns	9.530**	−13.200**	2.490ns	3.360*	−3.540*	−4.410**	5.520**	−5.120**

Table 5. Proximate, macro and micro-nutrient composition of 10 Bambara groundnut genotypes analysed in their cooked state, categorised as fastest and slowest cooking. *Protein (g 100 g⁻¹ DW), Fat (g 100 g⁻¹ DW), NDF (g 100 g⁻¹ DW), Ash (g 100 g⁻¹ DW) Moisture (%). *DW, Dry weight basis; NDF, Neutral detergent fibre.

g^{-1}) was lower than that of cooked BGN samples (5.95–8.16 g/100 g^{-1}) and was significantly different ($p < 0.001$). After cooking, the genotype Nav 4 showed the highest fat content recovery (3.16–6.77 g/100 g^{-1}). The result indicates that BGN mainly comprises Neutral Detergent Fibre (NDF) with a maximum of 46.8 and 64.09 g/100 g^{-1} for raw and cooked samples, respectively. The total mineral content (ash) of raw BGN was higher (4.18–5.23 g/100 g^{-1}) and significantly different ($p < 0.001$) from that of cooked BGN samples (2.5–4.85 g/100 g^{-1}).

The mineral concentration of raw and cooked BGN samples is shown in Tables 4 and 5. All the selected nutrients analysed exhibited significant differences except for P ($p = 0.309$) and Mg ($p = 0.22$). Iron was not detected in some cooked samples. An increase in the number of nutrients after cooking was observed in zinc (2.4–3.2 mg 100 g^{-1}) to (2.5–3.7 mg 100 g^{-1}), Na (0.00–0.0002 mg 100 g^{-1}) to (0.002–0.007 mg 100 g^{-1}), Cu (0.6–2.1 mg 100 g^{-1}) to (0.9–6.3 mg 100 g^{-1}) and Ca (0.0004–0.001 mg 100 g^{-1}) to (0.008–0.018 mg 100 g^{-1}) after cooking. Cooking also caused a reduction in the number of nutrients as observed in Fe from (1.7–9.6 mg 100 g^{-1}) to (0.00–2.9 mg 100 g^{-1}) and K (0.117–0.176 mg 100 g^{-1}) to (0.046–0.149 mg 100 g^{-1}). Iron and Zn were predominant minerals in raw BGN genotypes ranging from 1.7 to 9.6 mg 100 g^{-1} and 2.4–3.2 mg 100 g^{-1}, respectively.

Discussion

Seed size showed a significant and positive correlation with seed volume. Geethanjali, Rani[32] reported comparable findings for *Cicer arietinum* L, and Singh, Kaur[33] observed similar results for *Phaseolus mungo* L. Swelling capacity and swelling index were significantly positively corrected to the degree of lightness (L) $r = 0.367$ and $r = 0.389$ respectively. These results showed that light-coloured genotypes swelled more than dark-coloured genotypes. Light-coloured genotypes that swell more could cook faster because they imbibe water more efficiently, leading to quicker softening of tissues[28].

Hydration capacity was positively correlated to the hydration index, swelling capacity and swelling index (Fig. 4a). The findings of this study align with those of[28], indicating that seed coat colour impacts the structural and imbibitional characteristics of BGN seeds. Both hydration and swelling properties were significantly correlated to cooking time (Fig. 5a). Seeds with greater hydration and swelling properties cook fast due to (i) enhanced water absorption, (ii) improved heat transfer, (iii) reduced structural integrity and (iv) faster gelatinisation.

Seed size was also significantly correlated with cooking time; similar findings of a positive correlation between cooking time and seed size were reported. Smaller seeds have a less dense internal structure compared to larger seeds. A less dense structure allows water and heat to penetrate more efficiently throughout the seed, promoting faster cooking. Cooking time was significantly positively correlated with texture ($r = 0.96$). These results indicated that BGN genotypes that took longer to cook had a firmer texture. This implies that fast-cooking genotypes also give a better texture.

Seed size showed a significant positive correlation with cooking time, corroborating earlier findings by Santos, Carbas[34], who observed that larger seeds generally required longer cooking durations. This relationship may be attributed to size and internal structural density, as smaller seeds tend to possess less compact microstructure, facilitating more efficient water and heat penetration during thermal processing[30,35]. However, while these studies support the trend observed in our results, contrasting findings have been reported in other legumes, where cooking time was more strongly influenced by seed coat thickness and composition than size alone[36]. The relative influence of seed size may vary depending on species-specific characteristics or genetic variation within the crop.

Cooking time was also positively correlated with post-cooking texture ($r = 0.96$), indicating that genotypes requiring longer cooking times also exhibited firmer textures. This strong association may reflect slower starch gelatinization and delayed solubilization of cell wall components in these genotypes, which could be linked to genetic factors and differential seed maturity at harvest[36]. Furthermore, fast-cooking genotypes yielded softer textures, which are generally preferred in consumer acceptability studies[37]. Mubaiwa, Fogliano[22] highlighted that differences in texture and cooking performance among genotypes may also be influenced by agroecological conditions (temperature, soil nutrient availability) during seed development, which have been shown to affect hydration dynamics and seed hardness.

In our study, uniform cooking conditions were applied to all genotypes, minimizing environmental and procedural variability; hence, observed differences can be primarily attributed to inherent physicochemical properties and genetic background. This strengthens the reliability of the correlations and underscores the need to integrate seed structural traits into breeding programs that target reduced cooking time and improved sensory quality in BGN.

Variations in the nutritional composition of BGN genotypes amount from (i) environmental factors affecting plant growth[38], (ii) genetic diversity[39] and (iii) techniques used for nutrition analysis[40,41]. The protein concentration of all BGN genotypes increased after soaking and cooking, and these findings were in line with the report for common beans and chickpeas by[42]. The increase in protein content after cooking is attributed to the denaturing of some anti-nutritional factors, resulting in the release of nutrients[9,43].

Protein-energy malnutrition (PEM) is a major problem in developing countries[44–46]. This condition arises from a severe deficiency in protein and caloric intake, leading to health problems (stunted growth, weakened immunity, and increased susceptibility to infections). According to the World Health Organization (WHO), PEM affects millions of children and adults, contributing significantly to morbidity and mortality rates in low-income regions[47]. In this context, the study findings highlight the potential of BGN as a valuable nutritional resource. Bambara groundnut seeds are rich in protein, containing approximately 18–25% protein by dry weight, comparable to other legumes such as chickpeas and lentils[48]. This high protein content makes BGN an excellent dietary option to combat protein deficiencies, particularly in regions where protein-rich foods (meat and dairy) are economically inaccessible.

Fats play a crucial role in maintaining good health by providing a dense energy source and facilitating the absorption of fat-soluble vitamins and the synthesis of hormones[49]. In evaluating the cooking quality of BGN, the study observed a significant increase in fat content following soaking and cooking ($p < 0.001$). This enhancement in fat content post-cooking is consistent with the findings of Mazahib, Nuha[50], who reported similar outcomes for other legumes. Notably, despite the significant rise in fat levels, the overall fat content of cooked BGN remains within the recommended dietary allowance (RDA) range of 3–17 g 100 g^{-1}, ensuring its nutritional adequacy for consumption. These results are pivotal for breeding programs that optimise BGN for nutritional quality. The ability to increase fat content through cooking while maintaining it within safe and beneficial dietary limits highlights the potential of BGN as a functional food. This information is valuable for developing BGN varieties with enhanced cooking quality and nutritional profiles, aligning with improving food security and nutritional health in various populations.

The moisture content of dried legumes is crucial for determining their shelf life, product quality, and processing techniques[51]. The moisture content of the BGN genotypes decreased after cooking. These findings contradict Shanono and Muhammad[52], who observed a significant increase in moisture content after cooking. Although the moisture content of BGN samples increased after cooking, it was in the same range as recommended values (3–8%) for the extended storage of legumes. Significant disparities in the availability of selected mineral elements were observed between soaking and cooking, except for Mg and P. Specifically, there was a notable increase in Ca, Cu, Zn, and Na levels. In contrast, Fe levels experienced a significant decrease.

The disparities in mineral element availability between soaking and cooking can be attributed to distinct physicochemical changes during these processes[53]. Soaking leads to the leaching of soluble minerals, while cooking enhances the availability of some minerals by breaking down complexes and reducing anti-nutritional factors[54]. However, minerals like Fe may decrease due to leaching or loss in the cooking water. Magnesium and P levels remain relatively stable due to their chemical properties and interactions within the food matrix[55].

Conclusion

The Bambara groundnut genotypes evaluated in this study exhibited significant variation in physicochemical properties, enabling classification into five distinct cooking categories: A (soft-cooking), B (slightly soft-cooking), C (slightly hard-cooking), D (moderately hard-cooking), and E (hard-cooking). Genotypes such as DodR, BURKINA, ANKPA 4, TIGD, NAV 4, and several S19/Ankpa4 and IITA686/LunT lines were consistently classified as soft-cooking. In contrast, genotypes including UNISWA, SONGKHLA, DIP-C, EXSOCOTO, and others exhibited hard-cooking characteristics. These findings have clear implications for breeding programs. The soft-cooking genotypes represent promising parental lines for developing improved Bambara groundnut varieties with enhanced cooking quality—traits desirable for household consumption and agro-processing. Conversely, hard-cooking genotypes may offer utility in breeding for industrial applications requiring structural resilience, such as flour production or extrusion-based processing. Future research should focus on identifying and mapping key genomic regions or candidate genes controlling cooking time and texture through molecular and genomic approaches. Additionally, exploring gene–trait associations and the underlying biochemical mechanisms will be critical for marker-assisted selection. Optimizing cooking protocols for different genotype categories may also support product development and value chain expansion.

Data availability

The datasets used or analysed during the current study are available from the corresponding author upon reasonable request.

References

1. Tan, X. L. et al. Bambara groundnut: an underutilized leguminous crop for global food security and nutrition. *Front. Nutr.* **7**, 601496 (2020).
2. Ntundu, W. H. et al. Morphological diversity of Bambara groundnut [*Vigna subterranea* (L.) Verdc.] landraces in Tanzania. *Genet. Resour. Crop Evol..* **53**(2), 367–378 (2006).
3. Halimi, R. A. et al. The potential of the underutilized pulse Bambara groundnut (*Vigna subterranea* L.) for nutritional food security. *J. Food Compos. Anal.* **77**, 47–59 (2019).
4. Nyau, V. et al. Idenfication of nutraceutical phenolic compounds in Bambara groundnuts (*Vigna subterranea* L. Verdc) by HPLC-PDA-ESI-MS. *Br. J. Appl. Sci. Technol.* **6** (1), 77 (2015).
5. Oluwole, O. B. et al. Medicinal uses, nutraceutical potentials and traditional farm production of Bambara beans and pigeon pea. *Glob. J. Epidemiol. Public. Health.* **6**, 41–50 (2021).
6. Christian, P. & Smith, E. R. Adolescent undernutrition: global Burden, Physiology, and nutritional risks. *Ann. Nutr. Metab.* **72** (4), 316–328 (2018).
7. Diedericks, C. F. et al. Effect of processing on the microstructure and composition of Bambara groundnut (*Vigna subterranea* (L.) Verdc.) seeds, flour and protein isolates. *Food Hydrocoll.* **108**, 106031 (2020).
8. Wainaina, I. et al. Thermal treatment of common beans (*Phaseolus vulgaris* L.): factors determining cooking time and its consequences for sensory and nutritional quality. *Compr. Rev. Food Sci. Food Saf.* **20** (4), 3690–3718 (2021).
9. Vashishth, R. et al. Influence of cooking methods on antinutritional factors, oligosaccharides and protein quality of underutilized legume macrotyloma uniflorum. *Food Res. Int.* **143**, 110299 (2021).
10. Ficco, D. B. et al. Use of purple durum wheat to produce naturally functional fresh and dry pasta. *Food Chem.* **205**, 187–195 (2016).
11. Mestres, C., Briffaz, A. & Valentin, D. *Rice Cooking and Sensory quality, in Rice*, 385–426 (Elsevier, 2019).
12. Wood, J. A. Evaluation of cooking time in pulses: A review. *Cereal Chem.* **94** (1), 32–48 (2017).
13. Carmody, R. N. & Wrangham, R. W. The energetic significance of cooking. *J. Hum. Evol.* **57** (4), 379–391 (2009).
14. Zhang, H. et al. Effects of high hydrostatic pressure on nutritional composition and cooking quality of whole grains and legumes. *Innov. Food Sci. Emerg. Technol.* **83**, 103239 (2023).

15. Abdel-Aleem, W. M., Abdel-Hameed, S. M. & Latif, S. S. Effect of soaking and cooking on nutritional and quality properties of Faba Bean. *J. Food Dairy Sci.* **10**(10) (2019).
16. Atilola, B. *Product Attributes and Consumer Preference: The Case of Common Beans in Zambia* (2018).
17. Harouna, D. V. et al. Assessment of water absorption capacity and cooking time of wild Under-Exploited species towards their domestication. *Agronomy-Basel* **9** (9), 509 (2019).
18. Sofi, P. et al. Comparative evaluation of common bean (*Phaseolus vulgaris* L.) germplasm for seed physical and culinary traits. *J. Appl. Hortic.* **16** (1), 54–58 (2014).
19. Perera, D. et al. Hard-to-cook phenomenon in common legumes: Chemistry, mechanisms and utilisation. *Food Chem.* **415**, 135743 (2023).
20. Santos, G. G., Ribeiro & Maziero, S. M. Evaluation of common bean morphological traits identifies grain thickness directly correlated with cooking time. *Pesquisa Agropecuária Trop.* **46**, 35–42 (2016).
21. Saha, S. et al. Variability of nutritional and cooking quality in bean (*Phaseolus vulgaris* L) as a function of genotype. *Plant. Foods Hum. Nutr.* **64** (2), 174–180 (2009).
22. Mubaiwa, J. et al. Hard-to-cook phenomenon in Bambara groundnut (*Vigna subterranea* (L.) Verdc.) processing: options to improve its role in providing food security. *Food Rev. Int.* **33** (2), 167–194 (2017).
23. Oyeyinka, A. T. et al. Physical, nutritional and antioxidant properties of Zimbabwean Bambara groundnut and effects of processing methods on their chemical properties. *Int. J. Food Sci. Technol.* **52** (10), 2238–2247 (2017).
24. Martín-Cabrejas, M. A. et al. Changes in physicochemical properties of dry beans (*Phaseolus vulgaris* L.) during long-term storage. *J. Agric. Food Chem.* **45** (8), 3223–3227 (1997).
25. Azad, M. A. & Lebenthal, E. Role of rat intestinal glucoamylase in glucose polymer hydrolysis and absorption. *Pediatr. Res.* **28** (2), 166–170 (1990).
26. Asoegwu, S. et al. Physical properties of African oil bean seed (*Pentaclethra macrophylla*). *CIGR J.* (2006).
27. Yadav, U. et al. Physico-chemical, hydration, cooking, textural and pasting properties of different Adzuki bean (*Vigna angularis*) accessions. *J. Food Sci. Technol.* **55** (2), 802–810 (2018).
28. Mandizvo, T. & Odindo, A. O. Seed coat structural and imbibitional characteristics of dark and light coloured Bambara groundnut (*Vigna subterranea* L.) landraces. *Heliyon.* **5** (2), e01249 (2019).
29. Kinyanjui, P. K. et al. Hydration properties and texture fingerprints of easy- and hard-to-cook bean varieties. *Food Sci. Nutr.* **3** (1), 39–47 (2015).
30. Mandizvo, T., Odindo, A. O. & Mashilo, J. Nutrient composition and physical properties of Citron watermelon (*Citrullus lanatus* var. Citroides (L.H. Bailey) Mansf. Ex Greb.) seeds are related to seed coat visual appearance. *South. Afr. J. Bot.* **145**, 405–419 (2022).
31. Kurilenko, L. N. & Kostyreva, T. G. Determination of quantities of sodium and potassium taking into account their mutual influence in glass and zeolites using the method of flame atomic emission spectrometry. *Glass Phys. Chem.* **42** (3), 266–269 (2016).
32. Geethanjali, D., Rani, M. S. & Jayalakshmi, V. Genetic diversity analysis in Chickpea (*Cicer arietinum* L.) grown under rainfed and irrigated conditions for quality and yield attributing traits. *Indian J. Agric. Res.* **52** (6), 691–695 (2018).
33. Singh, N. et al. Physicochemical, cooking and textural characteristics of some Indian black gram (*Phaseolus mungo* L) varieties. *J. Sci. Food Agric.* **84** (9), 977–982 (2004).
34. Santos, C. S. et al. Relationship between seed traits and pasting and cooking behaviour in a pulse germplasm collection. *Crop Pasture Sci.* **69** (9), 892–903 (2018).
35. Deng, X. et al. Insight into the incredible effects of microwave heating: driving changes in the structure, properties and functions of macromolecular nutrients in novel food. *Front. Nutr.* **9**, 941527 (2022).
36. Bassett, A., Hooper, S. & Cichy, K. Genetic variability of cooking time in dry beans (*Phaseolus vulgaris* L.) related to seed coat thickness and the cotyledon cell wall. *Food Res. Int.* **141**, 109886 (2021).
37. Asiimwe, R. et al. Evaluating consumer preferences for reduced cooking time, taste and colour of beans in rural and urban communities in Uganda. *Agric. Food Secur.* **13**(1), 19 (2024).
38. Olanrewaju, O. S. et al. Genetic diversity and environmental influence on growth and yield parameters of Bambara groundnut. *Front. Plant. Sci.* **12**, 796352 (2021).
39. Mandizvo, T. & Odindo, A. O. Seed mineral reserves and vigour of Bambara groundnut (*Vigna subterranea* L.) landraces differing in seed coat colour. *Heliyon* **5** (5), e01635 (2019).
40. Mandizvo, T. & Odindo, A. O. Spectrophotometric quantification of phytic acid during embryogenesis in Bambara groundnut (*Vigna subterranea* L.) through phosphomolybdenum complex formation. *Emirates J. Food Agric.* **32** (11), 778–785 (2020).
41. Olanrewaju, O. S. et al. Variations of nutrient and antinutrient components of Bambara groundnut (*Vigna subterranea* L. Verdc.) seeds. *J. Food Qual.* **2022**. (2022).
42. Wang, N. et al. Effect of cooking on the composition of beans (*Phaseolus vulgaris* L.) and Chickpeas (*Cicer arietinum* L). *Food Res. Int.* **43** (2), 589–594 (2010).
43. Rahate, K. A., Madhumita, M. & Prabhakar, P. K. Nutritional composition, anti-nutritional factors, pretreatments-cum-processing impact and food formulation potential of Faba bean (*Vicia faba* L.): A comprehensive review. *Lwt-Food Sci. Technol.* **138**, 110796 (2021).
44. Batool, R. et al. Protein-energy malnutrition: A risk factor for various ailments. *Crit. Rev. Food Sci. Nutr.* **55** (2), 242–253 (2015).
45. Ahmed, T. et al. *Protein-Energy Malnutrition in Children, in Hunter's Tropical Medicine and Emerging Infectious Diseases*, 1034–1041 (Elsevier, 2020).
46. Cheng, A. et al. In search of alternative proteins: unlocking the potential of underutilized tropical legumes. *Food Secur.* **11** (6), 1205–1215 (2019).
47. Chuwa, C., Dhiman, A. K. & Kathuria, D. General overview of malnutrition under five children in low income countries and solution to mitigate. *Curr. J. Appl. Sci. Technol.* **39** (48), 466–482 (2020).
48. Oyeyinka, S. A. & Oyeyinka, A. T. A review on isolation, composition, physicochemical properties and modification of Bambara groundnut starch. *Food Hydrocoll.* **75**, 62–71 (2018).
49. Bennasir, H., Sridhar, S. & Abdel-Razek, T. T. Vitamin A from physiology to disease prevention. *Int. J. Pharm. Sci. Rev. Res.* **1** (1), 68–73 (2010).
50. Mazahib, A. et al. Some nutritional attributes of bambara groundnut as influenced by domestic processing. (2013).
51. Oghbaei, M. & Prakash, J. Effect of primary processing of cereals and legumes on its nutritional quality: a comprehensive review. *Cogent. Food Agric.* **2**(1), 1136015 (2016).
52. Shanono, I. M. & Muhammad, Y. Y. Effect of cooking on proximate and anti-nutritional content of Bambara groundnut. *J. Adv. Food Sci. Technol.* **2** (4), 176–180 (2015).
53. Hotz, C. & Gibson, R. S. Traditional food-processing and preparation practices to enhance the bioavailability of micronutrients in plant-based Diets1. *J. Nutr.* **137** (4), 1097–1100 (2007).
54. Oghbaei, M. & Prakash, J. Effect of dehulling and cooking on nutritional quality of Chickpea (*Cicer arietinum* L.) germinated in mineral fortified soak water. *J. Food Compos. Anal.* **94**, 103619 (2020).
55. Parada, J. & Aguilera, J. Food microstructure affects the bioavailability of several nutrients. *J. Food Sci.* **72** (2), R21–R32 (2007).

Acknowledgements

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A.R.: conceptualization, investigation and writing original draft. L.G.: conceptualization, formal analysis, and writing of the original draft. T.M.: formal analysis and data curation. A.I.S.: conceptualization, formal analysis, writing the original draft. T.M.: manuscript reviewing. F.M.: manuscript reviewing. S.M.: reviewing. H.C.: manuscript reviewing. J.S.: reviewing. T.M.: conceptualization, writing original and formal analysis.

Declarations

Competing interests

The authors declare no competing interests.

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