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Multivariate statistical analysis applied to physical properties of soybean seeds cultivars on the post-harvest

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ABSTRACT. To consider the different characteristics of soybean seeds for designing and regulating the post-harvest equipment, we evaluated the similarities in the physical properties of soybean cultivars in this study. Two-hundred soybean seeds from 40 genetically modified cultivars were collected in packages to measure the physical properties of the seeds. First, principal component analysis was performed to verify the interrelationships between the variables and soybean cultivars. Next, a boxplot was constructed for each variable, considering the groups obtained after analyzing the main components. Finally, a scatterplot containing the Pearson's correlations between the variables was constructed. We identified two clusters of cultivars: C1 and C2. The unit-specific mass was the physical property that contributed the most to the formation of C1, whereas the other physical properties contributed to the formation of C2. Soybean cultivars comprising C1 were similar to each other only in unit specific mass, and the cultivars allocated to group C2 were similar according to all the other properties evaluated. These results can serve as a guideline for genotype selection for soybean genetic improvement to minimize variations in the physical characteristics of the seeds and obtain greater efficiency in the processing stages. Thus, the equipment manufacturing industry and seed processing units can implement projects and equipment adjustments to manage the post-harvest and seeding processes of soybean seeds efficiently.

Keywords: equipment manufacturing industry; post-harvest loss reductions; process optimization; seed processing units; soybean seed quality.

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Introduction

The use of precision agriculture techniques and the adoption of different soybean cultivars can increase soybean yield. Genetic breeding has enabled the development of a large number of soybean cultivars. Until May 2011, 823 soybean cultivars were listed in the National Register of Cultivars in Brazil out of which 502 cultivars were conventional and 321 were transgenic. The number of cultivars recorded in the National Register of Cultivars in January 2018 was 118% higher than that in 2011; out of the 1799 registered cultivars, 1234 cultivars were transgenic and 565 were conventional (Botelho, Granella, Botelho, & Garcia, 2015; Nikoobin, Mirdavardoost, Kashaninejad, & Soltani, 2009; Teixeira, Hampton, & Moot, 2020).

Post-harvest operations are affected by the variations in soybean genetic material, especially the physical variations in the seeds (Nikoobin, et al., 2009; Lima et al., 2021). Because of technological advancement, genetic improvement, and the production of different soybean seed cultivars, a variety of soybean seed lots with different physical characteristics are available. Hence, for greater operational yield in the post-harvest units, reduction of losses, and gains in quality, the development of flexible equipment (in terms of regulation and control) that consider the difference in the physical characteristics of seed cultivars is necessary (Araújo et al., 2020; Oliveira, Coradi, Alves, Teodoro, & Alvarez, 2021).

The composition and geometric shapes of seeds often interfere with the design, sizing, and regulation of machines used for handling, drying, storing, processing, and sowing (Jaques et al., 2022). The physical properties of a seed must be known for designing harvesting machines; ducts; discharge ramps; fans; sieves; and drying and aeration systems, determining the static capacity of the silos and conveyor belts, sizing the hoppers, separating, classifying, processing, handling, and storing (Nikoobin et al., 2009; Fernández-Fernández, Marcelo, Valenciano, López, & Pastrana, 2020). Studies conducted to evaluate the physical properties of the seeds of several crops have reported that uniformly sized seed lots ensures better post-harvest operation performance, seed conservation, and quality (Payman, Ajdadi, & Bagheri, 2011; Mir, Bosco, & Sunooj, 2013).

For a more detailed analysis of the physical properties of a group of soybean seed cultivars multivariate statistical techniques must be applied (Antonucci et al., 2020). Using multivariate data analysis, the behavioral profile of a group exposed to the same phenomenon can be described based on all variables and their interactions (Mukasa et al., 2022). Thus, multiple measures can be analyzed simultaneously, which provide a deeper, more accurate, and more meticulous behavioral analysis. Recently, principal component analyses and Pearson correlations were adopted in some studies to investigate the drying and storage of seed cultivars and explain the results better (Coradi, Dubal, Bilhalva, Fontoura, & Teodoro, 2020a; Coradi et al., 2020b; Oliveira et al., 2021).

Thus, for considering the different characteristics of soybean-cultivar seeds and the different post-harvest operations and equipment, the aim of the study is to evaluate the similarity of the physical properties of seed cultivars and use it as a guiding parameter to decide the design and control of post-harvest equipment using multivariate statistical analysis.

Material and methods

In this study, we characterized the physical properties of six-hundred soybean seeds from each of 40 cultivars. The seeds were from heterogeneous lots produced and sown in the central-western region of Brazil. The soybean seeds from each sample harvested in 2019, 2020, and 2021 were stored in three different packages (top, middle, and bottom); each package contained 200 seeds. The shaken of the packages normally provides the accommodates smaller, medium, and larger seeds in different positions in the package. Thus, three sample points (top, middle, and bottom) were defined to characterize the seed lot better. In total, 136 lots of soybean seeds cultivars were evaluated. Seed size was determined by measuring the length, width, and thickness of the seed using a 0.01 mm resolution caliper, while the other physical properties were calculated using the equations listed in Table 1 (Mohsenin, 1989).

Table 1. Equations for determination of physical properties of soybean seeds.

Physical properties of soybean seeds	Equation
$V = \frac{\pi LWT}{6}$	(1)
$ASM = {UM}/{V}$	(2)
$UM = {ASM}/{(P-1)}$	(3)
$PA = 3.14AB$	(4)
$ED = (LWT)^{1/3}$	(5)
$SA = 3.14(ED)^2$	(6)
$SVR = \frac{SA}{V}$	(7)
$Sp = \frac{(\pi LWT)^{1/3}}{L}$	(8)
$FC = 5.31 - 4.88Sp$	(9)
$C_r = {PA}/{CA}$	(10)
$P = \left[1 - \left(\frac{ASM}{USM}\right)\right]$	(11)
$RA = arctg(hr^{-1})$	(12)

Volume (*V*, mm³), Length (*L*, mm), Width (*W*, mm), Thickness (*T*, mm), Circularity (*Cr*), Sphericity (*Sp*), Equivalent diameter (*ED,* mm), Projected area (*PA,* mm²), Surface area (*SA*, mm), Surface-to-volume ratio (*SVR*), Circumscribed area (CA, mm²), Friction coefficient (*FC*), Unit mass (*UM*, kg m^{-3}), Unit specific mass (*USM*, kg m^{-3}), Apparent specific mass (*ASM*, kg m^{-3}), Rest angle (*RA*, °), and Porosity (*P*, %), *A* is major semi-axis (mm), *B* is minor semi-axis (mm), *h* is height, *r* is ratio.

To evaluate the results, variance analysis was performed. The means were compared using the Scott-Knott test at 5% probability and we used the Sisvar 5.6 software to define the largest, intermediate-larger, intermediate-smaller, and smaller seeds.

Principal component analysis (PCA) was performed using standardized variables. A biplot was constructed with the first two principal components corresponding to due the accumulated variation in the components. In the biplot, two clusters were defined using the k-means algorithm, which groups observations into a cluster whose centroid is the closest to the observations until no significant variation is found in the minimum distance between each observation and the centroid.

A boxplot was constructed for each variable based on the groups obtained after analyzing the main components. The components were analyzed with the aid of the "qgraph", "ggfortify", and "ggplot2" packages in software R. Finally, for each cluster formed, a scatterplot containing the Pearson's correlations between the variables was constructed. A t-test was conducted to verify the significance of the correlations at 5% probability.

Results

The average values of physical properties of the 40 soybean seed cultivars are listed in Tables 2 and 3. The average, maximum, and minimum seed lengths were 8.116, 9.300 (in cultivar FLECHA IPRO), and 7.040 mm (in cultivar NS 7447), respectively. The average, maximum, and minimum seed widths were 7.464, 8.180 (FLECHA IPRO), and 6.620 mm (NS 7447), respectively. The average, maximum, and minimum seed thicknesses were 6.890, 7.900 (FLECHA IPRO), and 6.175 mm (NS 6823 RR), respectively.

Table 2. Evaluation of physical properties of different soybean seed cultivars.

Cultivars	*L* (mm)	W (mm)	T (mm)	*V* (mm^3)	C_r	*Sp*	*ED* (mm)	*PA* (mm^2)
68H0 RSF IPRO	8.695 c	8.030 b	7.395 d	270.210 b	0.924 l	0.904 l	7.857 b	54.80 c
6968 RSF RR	8.080 r	7.615 o	6.730 w	216.708 v	0.942 j	0.904 l	7.305 s	48.30 p
7166 RSF	7.970 u	7.615 o	6.675 z	212.011 z	0.955 g	0.910 k	7.253 w	47.64 u
3980 RR	8.315 l	7.235 v	6.315 h1	198.817 c1	0.870 w	0.854 u	7.101 z	47.22 y
6139 RR	8.275 m	7.310 t	6.730 w	213.049 y	0.883 t	0.878 q	7.264 v	47.48 v
ATRIA RR	8.575 f	7.690 j	6.455 g1	222.759 q	0.897 p	0.860 t	7.372 o	51.76 i
GURIA RR	8.260 n	7.640 m	6.650 a1	219.621 r	0.925 l	0.888 o	7.338 p	49.53 m
SMAMBA RR	8.145 q	8.025 c	7.690 b	263.052 c	0.985 b	0.956 b	7.788 c	51.31 j
BRS 7380 RR	8.445 i	8.000 d	7.335 f	259.339 f	0.947 i	0.918 j	7.751 e	53.03 e
2728 IPRO	8.150 p	7.465 s	7.335 f	233.543 k	0,916 n	0.919 i	7.488 j	47.75 s
2687 RR	8.660 d	7.680 k	6.875 s	239.293 i	0.887 s	0.872 r	7.548 h	52.20 h
2737 RR	8.145 q	7.680 k	7.115 j	232.919 l	0.943 j	0.919 i	7.481 k	49.10 o
CZ26 B42 IPRO	7.950 w	7.900 f	7.075 n	232.541 m	0.994 a	0.941 d	7.477 l	49.30 n
FLECHA IPRO	9.300 a	8.180 a	7.900 a	314.515 a	0.880 u	0.888 o	8.261 a	59.71 a
GXM 7148 IPRO	7.645 h1	7.485 r	7.175 h	214.867 w	0.979 c	0.953 c	7.285 t	44.92 b1
GXM 8372 IPRO	7.955 v	7.600 p	6.930 r	219.263 s	0.955 g	0.922 h	7.334 q	47.46 w
8573 RR	7.925 y	7.675 l	7.080 m	225.366 n	0.968 e	0.934 e	7.400 m	47.74 t
74178 IPRO EXTRA	7.970 u	7.710 i	7.000 p	225.107 o	0.967 e	0.928 g	7.398 m	48.23 q
CERTA IPRO	7.775 e1	7.305 u	6.505 d1	193.351 f1	0.940 k	0.905 l	7.036 c1	44.58 d1
ULTRA IPRO	8.465 h	7.960 e	7.360 e	259.535 e	0.940 k	0.916 j	7.753 e	52.89 f
KWS RK 6813 RR2	8.465 h	7.135 x	6.300 j1	199.131 b1	0.843 x	0.839 w	7.104 y	47.41 x
KWS RK 6813 RR	7.805 d1	7.005 a1	6.300 j1	180.260 l1	0.898 p	0.881 p	6.875 i1	42.91 i1
M7739 IPRO	8.390 j	7.005 a1	7.090 l	218.069 u	0.835 y	0.873 r	7.320 r	46.13 a1
5947 IPRO	7.685 g1	7.075 y	6.720 y	191.213 h1	0.921 m	0.912 k	7.010 e1	42.68 j1
7337 RR	7.995 t	7.140 w	6.725 x	200.903 a1	0.893 q	0.891 n	7.125 x	44.81 c1
M6410	7.940 x	7.520 q	6.835 u	213.577 x	0.947 i	0.916 j	7.270 u	46.87 z
NS 7007 IPRO	8.995 b	7.850 g	7.105 k	262.551 d	0.873 v	0.865 s	7.783 d	55.42 b
NS 6823 RR	8.640 e	7.850 g	6.175 k1	219.179 t	0.909 o	0.849 v	7.333 q	53.24 d
NS 7505 IPRO	8.155 o	7.850 g	7.280 g	243.895 h	0.963 f	0.931 f	7.596 g	50.25 l
DESAFIO	8.495 g	7.850 g	7.125 i	248.654 g	0.924 l	0.900 m	7.645 f	52.34 g
TMG 1180GX RR	7.050 j1	6.845 e1	6.305 i1	159.230 n1	0.971 d	0.936 e	6.599 k1	37.88 m1
TMG 7062 IPRO	8.030 s	7.635 n	6.985 q	224.114 p	0.951 h	0.920 i	7.387 n	48.12 r
8473 RR	8.380 k	7.750 h	7.005 o	238.085 j	0.925 l	0.899 m	7.536 i	50.98 k
TMG 1264 RR	7.885 b1	7.075 y	6.605 b1	192.832 g1	0.897 p	0.891 n	7.029 d1	43.79 e1
98Y30	7.905 a1	6.990 c1	6.750 v	195.192 e1	0.884 t	0.893 n	7.058 b1	43.37 g1
98Y52	7.865 c1	7.000 b1	6.855 t	197.507 d1	0.890 r	0.901 m	7.085 a1	43.21 h1
96Y90	7.915 z	7.045 z	6.500 e1	189.681 i1	0.890 r	0.883 p	6.991 f1	43.77 f1
8579 RSF	7.770 f1	6.855 d1	6.485 f1	180.766 k1	0.882 u	0.886 o	6.881 h1	41.81 k1
2686 IPRO	7.550 i1	6.680 f1	6.580 c1	173.671 m1	0.885 t	0.899 m	6.791 j1	39.59 l1
NS 7447	7.040 k1	6.620 g1	7.540 c	183.899 j1	0.940 k	0.983 a	6.920 g1	36.58 n1
Average	8.116	7.464	6.890	219.457	0.920	0.903	7.321	47.657

Volume (*V*, mm^3), Length (*L*, mm), Width (*W*, mm), Thickness (*T*, mm), Circularity (*Cr*), Sphericity (*Sp*), Equivalent diameter (*ED*, mm), Projected area (*PA*, mm^2), The Scott-Knott test was used. Means followed by lowercase in the column for each cultivar, do not differ at 1% probability.

Table 3. Evaluation of physical properties of different soybean seed cultivars (Continued Table 2)

Cultivars	*SA* (mm²)	*SVR*	*FC*	*UM* (g)	*USM* (kg m⁻³)	*ASM* (kg m⁻³)	*RA* (°)	*P* (%)
68H0 RSF IPRO	193.84 b	0.717 v	1.090 u	0.230 c	903.114 h1	713.67 c1	22.383 y	40.333 f
6968 RSF RR	167.57 v	0.773 l	1.168 p	0.186 k	904.848 g1	711.92 e1	22.663 s	35.667 t
7166 RSF	165.17 z	0.779 j	1.138 r	0.151 q	886.678 l1	718.88 s	23.777 j	39.000 j
3980 RR	158.31 c1	0.796 h	1.672 c	0.161 o	1028.440 m	705.82 j1	24.123 h	39.667 h
6139 RR	165.70 y	0.778 j	1.902 a	0.194 i	813.679 n1	705.140k1	26.303 c	36.500 q
ATRIA RR	170.65 q	0.766 n	1.592 d	0.184 l	928.940 d1	712.79 d1	23.987 i	42.000 d
GURIA RR	169.06 r	0.770 m	1.316 i	0.179 m	890.156 j1	722.54 k	21.720 f1	43.000 b
SMAMBA RR	190.44 c	0.724 u	1.212 m	0.237 b	918.069 e1	776.35 b	22.340 z	43.833 a
BRS 7380 RR	188.66 f	0.727 t	0.971 x	0.210 d	987.591 p	706.01 h1	24.170 g	37.000 p
2728 IPRO	176.05 k	0.754 p	0.997 w	0.179 m	930.765 c1	721.38 n	21.717 g1	37.000 p
2687 RR	178.90 i	0.748 q	1.432 f	0.193 i	974.159 u	729.99 f	23.533 k	39.333 i
2737 RR	175.74 l	0.755 p	0.997 w	0.186 k	971.282 x	715.28 y	24.170 g	37.000 p
CZ26 B42 IPRO	175.56 m	0.755 p	0.793 e1	0.194 i	987.771 o	715.72 w	21.567 i1	43.000 b
FLECHA IPRO	214.27 a	0.681 w	1.202 n	0.251 a	962.074 z	783.03 a	25.580 d	43.000 b
GXM 7148 IPRO	166.63 w	0.776 k	0.661 g1	0.193 i	979.720 s	706.86 g1	23.033 p	39.333 i
GXM 8372 IPRO	168.87 s	0.770 m	0.973 x	0.178 m	973.910 v	727.72 i	22.170 a1	39.000 j
8573 RR	171.96 n	0.763 o	0.838 d1	0.206 e	901.020 i1	732.05 d	21.603 h1	38.667 k
74178 IPRO EXTRA	171.83 o	0.763 o	0.917 z	0.178 m	973.646 w	714.48 a1	24.847 f	38.000 m
CERTA IPRO	155.42 f1	0.804 f	1.179 o	0.158 p	1045.720 l	727.50 j	22.157 b1	40.333 f
ULTRA IPRO	188.75 e	0.727 t	0.950 y	0.183 l	910.941 f1	717.79 u	26.320 b	37.333 o
KWS RK 6813 RR2	158.47 b1	0.796 h	1.753 b	0.144 r	890.097 k1	705.94 i1	28.683 a	39.333 i
KWS RK 6813 RR	148.39 l1	0.823 c	1.456 e	0.210 d	1649.155 a	704.53 l1	22.600 v	40.667 e
M7739 IPRO	168.27 u	0.772 l	1.434 f	0.207 e	1009.928 n	711.44 f1	21.130 j1	39.333 i
5947 IPRO	154.29 h1	0.807 e	1.111 t	0.151 q	982.014 q	731.70 e	22.387 x	37.833 n
7337 RR	159.40 a1	0.793 i	0.750 f1	0.170 n	1117.630 k	714.58 z	23.293 n	37.000 p
M6410	165.97 x	0.777 k	0.650 h1	0.178 m	1166.406 h	719.24 r	25.277 e	40.333 f
NS 7007 IPRO	190.20 d	0.724 u	0.850 c1	0.149 q	936.468 b1	722.13 l	23.353 m	39.667 h
NS 6823 RR	168.83 t	0.770 m	1.060 v	0.118 s	978.605 t	728.79 h	23.513 l	40.333 f
NS 7505 IPRO	181.17 h	0.743 r	0.872 b1	0.201 g	949.898 a1	714.02 b1	21.747 e1	40.333 f
DESAFIO	183.49 g	0.738 s	1.151 q	0.212 d	966.867 y	739.37 c	20.857 l1	36.333 r
TMG 1180GX RR	136.73 n1	0.859 a	0.915 z	0.115 t	1131.251 j	728.88 g	22.640 u	42.833 c
TMG 7062 IPRO	171.33 p	0.764 o	0.998 w	0.191 j	980.769 r	720.03 o	21.903 d1	36.333 r
8473 RR	178.31 j	0.749 q	1.131 s	0.206 e	845.507 m1	598.7 m1	20.327 m1	36.000 s
TMG 1264 RR	155.15 g1	0.805 f	1.310 j	0.206 e	1302.751 c	732.05 d	22.650 t	39.667 h
98Y30	156.40 e1	0.801 g	1.292 k	0.204 f	1216.030 g	719.32 q	23.023 r	37.000 p
98Y52	157.62 d1	0.798 h	1.204 n	0.199 h	1158.139 i	717.56 v	22.057 c1	38.333 l
96Y90	153.47 i1	0.809 e	1.400 g	0.204 f	1312.412 b	721.43 m	23.030 q	38.333 l
8579 RSF	148.67 k1	0.822 c	1.393 h	0.178 m	1277.212 d	718.43 t	22.560 w	39.667 h
2686 IPRO	144.79 m1	0.834 b	1.264 l	0.197 h	1242.014 e	719.78 p	23.233 o	40.000 g
NS 7447	150.36 j1	0.818 d	0.878 a1	0.183 l	1237.346 f	715.29 x	20.940 k1	40.000 g
Average	168.622	0.773	1.147	0.186	1030.576	718.708	23.084	39.208

Surface area (*SA*, mm), Surface-to-volume ratio (*SVR*), Friction coefficient (*FC*), Unit mass (*UM*, kg m⁻³), Unit specific mass (*USM*, kg m⁻³), Apparent specific mass (*ASM*, kg m⁻³), Rest angle (*RA*, º), and Porosity (*P*, %). The Scott-Knott test was used. Means followed by lowercase in the column for each cultivar, do not differ at 1% probability.

The average, maximum, and minimum seed volumes were 219.447, 314.515 (FLECHA IPRO), and 159.230 mm³ (TMG 1180GX RR), respectively. The average, maximum, and minimum seed roundness were 0.920, 0.994 (CZ26 B42 IPRO), and 0.835 (1180GX RR), respectively. The average, maximum, and minimum seed sphericities were 0.903, 0.983 (NS 7447), and 0.839 (KWS RK 6813 RR2), respectively. The average, maximum, and minimum equivalent diameters of the seeds were 7.321, 8.261 (FLECHA IPRO), and 6.599 mm (TMG 1180GX RR), respectively.

The projected area of seed cultivars averaged to 47.65 mm² and ranged from 59.71 in FLECHA IPRO to 36.58 mm² in cultivar NS 7447. The surface area of the seed cultivars averaged to 168.62 mm² and ranged from 214.27 in the FLECHA IPRO cultivar to 136.73 mm² in the TMG 1180GX RR cultivar. The surface-volume ratio averaged 0.773 and ranged from 0.834 in 2686 IPRO to 0.681 in FLECHA IPRO. The friction coefficient as a function of seed displacement averaged to 1.147 and ranged from 1.902 in cultivar 6139 RR to 0.650 in cultivar M6410.

The unit mass of seeds averaged to 0.186 g and ranged from 0.251 in cultivar FLECHA IPRO to 0.115 g in cultivar TMG 1180GX RR. The unit-specific mass of the seeds averaged to 1030.67 kg m⁻³ and varied from 1649.155 in cultivar KWS RK 6813 RR to 813.679 kg m⁻³ in cultivar 6139 RR. The apparent specific mass of the soybean cultivars averaged to 718.70 kg m^{-3} and ranged from 783.030 to 598.723 kg m^{-3} in cultivars FLECHA IPRO and 8473 RR, respectively. The resting angle averaged to 23.08° and ranged from 28.68° to 20.32° in cultivars KWS RK 6813 RR2 and 8473 RR, respectively. The average, maximum, and minimum porosities of the seeds were 39.20, 43.83 (in cultivar MAMBA RR), and 36% (in cultivar 8473 RR), respectively.

As shown in Table 4, the seed lots of the different cultivars varied in their physical properties. Hence, the seeds could be characterized into four groups: larger seeds (LS), intermediate-larger seeds (ILS), intermediate-smaller seeds (ISS), and smaller seeds (SS). The ILS were predominant, followed by the LS, ISS, and SS. The seeds from FLECHA IPRO, 6139 RR, and MAMBA RR cultivars were larger seeds and those from NS 7447, 2686 IPRO, and 8473 RR cultivars were smaller seeds, while the other cultivars had seeds of average sizes.

Table 4. Percentage of larger seeds (LS), intermediate-larger seeds (ILS), intermediate-smaller seeds (ISS), smaller seeds (SS) according to the results of Tables 2 and 3.

Physical properties	LS (%)	ILS (%)	ISS (%)	SS (%)
L	2.5	47.5	50	0.0
W	12.5	75.0	12.5	0.0
T	42.5	57.5	0.0	0.0
V	2.5	30.0	35.0	32.5
Cr	62.5	37.5	0.0	0.0
Sp	55.0	45.0	0.0	0.0
ED	2.5	82.5	15.0	0.0
PA	30.0	62.5	7.5	0.0
SA	20.0	45.0	32.5	2.5
SVR	25.0	72.5	2.5	0.0
FC	10.0	35.0	55.0	0.0
UM	37.5	57.5	5.0	0.0
USM	35.0	52.5	12.5	0.0
ASM	5.0	22.5	72.5	0.0
RA	22.5	77.5	0.0	0.0
P	35.0	65.0	0.0	0.0

Volume (*V*, mm^3), Length (*L*, mm), Width (*W*, mm), Thickness (*T*, mm), Circularity (*Cr*), Sphericity (*Sp*), Equivalent diameter (*ED,* mm), Projected area (*PA,* mm^2), Surface area (*SA*, mm), Surface-to-volume ratio (*SVR*), Friction coefficient (*FC*), Unit mass (*UM*, kg m^{-3}), Unit specific mass (*USM*, kg m^{-3}), Apparent specific mass (*ASM*, kg m^{-3}), Rest angle (*RA*, º), and Porosity (*P*, %).

The seeds from cultivar UNIGEL 8473 RR Desafio (intermediate-larger seeds) exhibited considerable variation in apparent specific mass and porosity, while those from cultivar KWSRK 6813 RR (intermediate-smaller seeds) showed considerable variation in unit specific mass and angle of repose. The unit masses of cultivars FLECHA IPRO, NS 6823 RR, and TMG 1180GX RR were approximately the same and differed from that of all other cultivars. The coefficient of friction in cultivar AVANTSEED 96139 RR (intermediate-smaller seeds) was significantly different from that of the other cultivars.

The cultivar AVANTSEED SMANBA RR seeds (large seeds) had a higher porosity than others did. Seed lots need to be uniform for the optimal control of the post-harvest equipment; hence, three soybean cultivars exhibiting large size variations were separated to improve sowing quality and grain distribution. The length, width, and sphericity the seeds from cultivar UNIGEL NS 7447 differed from that of the other cultivar seeds, while the highest variations in thickness, volume, equivalent diameter, projected area, surface area, area ratio, and surface/volume, were found in the FLECHA IPRO cultivar seeds. The cultivar M7739 IPRO seeds showed the highest variations in circularity.

The results obtained using PCA is presented in Figure 1. Two clusters (C1 and C2) were obtained. Cluster 1 (C1) consisted of the 3980 RR, 6139 RR, CERTA IPRO, KWS RK 6813 RR2, KWS RK 6813 RR, M7739 IPRO, 5947 IPRO, 7337 RR, TMG 1180 GXRR, TMG 1264 RR, 98Y30, 98Y52, 96Y90, 8579 RSF, 2686 IPRO, and NS 7447 cultivars.

The cultivars 68H0 RSF IPRO, 6968 RSF RR, 7166 RSF, ATRIA RR, GURIA RR, MAMBA RR, BRS 7380 RR, 2728 IPRO, 2687 RR, 2737 RR, CZ26 B42 IPRO, FLECHA IPRO, GXM 7148 IPRO, GXM 8372 IPRO, 8573 RR, 74178 IPRO EXTRA, ULTRA IPRO, M6410, NS 7007 IPRO, NS 6823 RR, NS 7505 IPRO, DESAFIO, TMG 7062 IPRO, and 8473 RR comprised Cluster 2 (C2). The unit specific mass (USM) was the physical property that contributed the most to the formation of C1.

This finding was supported by the boxplot of physical properties, which showed a marked difference between the USMs of the clusters; cluster C1 exhibited a higher mean USM (Figure 2). The surface-to-volume ratio (SVR) and friction coefficient (FC) were the other properties for which C1 showed a higher mean than that of C2; however, they did not contribute to the formation of C1.

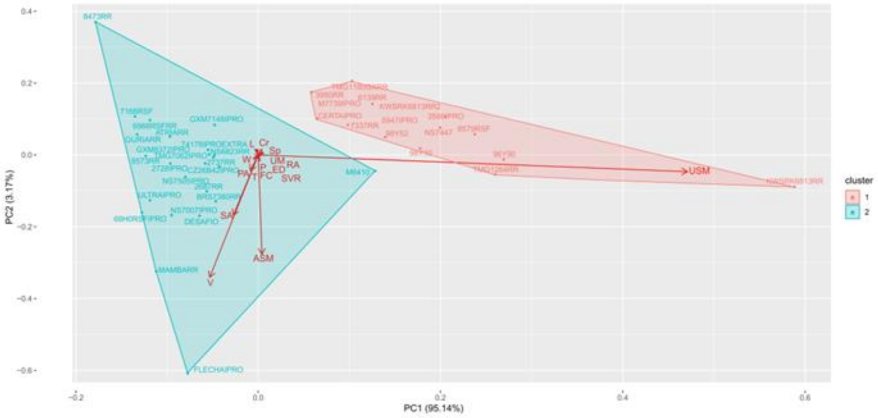

Figure 1. Principal component analysis for the physical seed properties volume (*V*, mm³), length (*L*, mm), width (*W*, mm), thickness (*T*, mm), circularity (*Cr*, mm), sphericity (Sp), equivalent diameter (*ED,* mm), projected area (*PA*, mm²), surface area (*SA*, mm), surface-to-volume ratio (*SVR*), friction coefficient (*FC*), unit mass (*UM*, kg m^{-3}), unit specific mass (*USM*, kg m^{-3}), apparent specific mass (*ASM*, kg m^{-3}), rest angle (*RA*, º), and porosity (*P*, %), evaluated in 40 soybean cultivars.

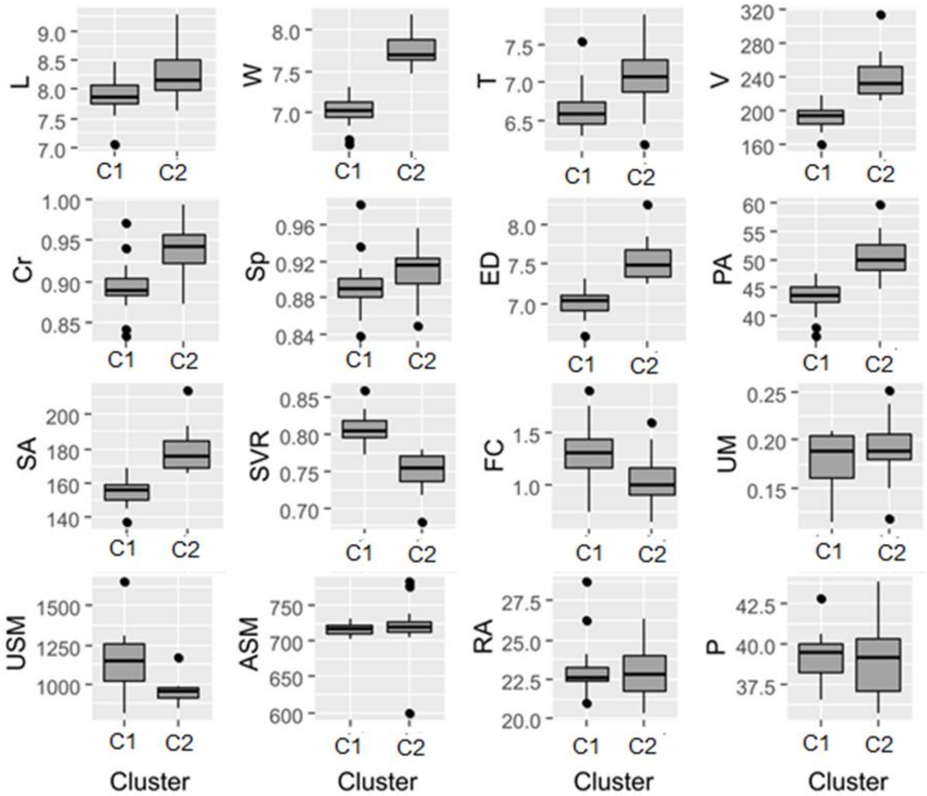

Figure 2. Boxplot for the physical seed properties volume (*V*, mm³), length (*L*, mm), width (*W*, mm), thickness (*T*, mm), circularity (*Cr*, mm), sphericity (Sp), equivalent diameter (*ED*, mm), projected area (*PA*, mm²), surface area (*SA*, mm), surface-to-volume ratio (*SVR*), friction coefficient (*FC*), unit mass (*UM*, kg m^{-3}), unit specific mass (*USM*, kg m^{-3}), apparent specific mass (*ASM*, kg m^{-3}), rest angle (*RA*, º), and porosity (*P*, %), as function of the cluster formed by Cluster Analysis.

Other physical properties contributed to the formation of C2. As can be observed from Figure 2, C2 had higher means for length (L), width (W), thickness (T), volume (V), circularity (Cr), sphericity (Sp), equivalent diameter (ED), and projected and surface areas (PA and SA, respectively). Hence, C2 cultivars had larger seeds than those allocated to C1. Based on the results provided by PCA and the boxplot of the physical properties, we inferred that the soybean cultivars comprising C2 were more similar to each other according to all the properties assessed, except for USM. USM was the property by which the cultivars allocated to the C1 group were the most similar.

The similarity results suggested that a certain group of soybean-cultivar seed lots had a higher homogeneity with respect to the physical properties. In this sense, the cultivars allocated to C2 were homogeneous in terms of volume, length, width, thickness, circularity, sphericity, equivalent diameter, projected area, surface area, SVR, friction coefficient, unit mass, apparent specific mass, rest angle, and porosity of seeds, whereas the C1-cultivars had a greater heterogeneity in terms of these properties.

In the scatterplot, several physical properties of the seeds in the two groups (C1 and C2) were found to be correlated (Figure 3). A strong positive correlation was observed between VxPA, VxED, VxSA, EDxSA, EDxW, WxV, PAxL, PAxW, and LxV.

Moderate positive correlations were observed between LxED, EDxT, TxV, and CrxSp. In contrast, significant negative correlations were found between WxSVR, PAxSVR, VxSVR, EDxSVR, and SVRxSA. Further, moderate negative correlations were observed between SVRxL, SVRxT, CrxFC, SpxFC, USMxW, USMxPA, and USMxEd. The other correlations were insignificant; hence, they are not mentioned here. From these results, we inferred that a positive relationship existed between the size-related properties, namely, volume, length, width, projected and surface areas, equivalent diameter, and thickness. The other physical properties of the seed, such as those related to shape and mass, showed negligible to zero correlation.

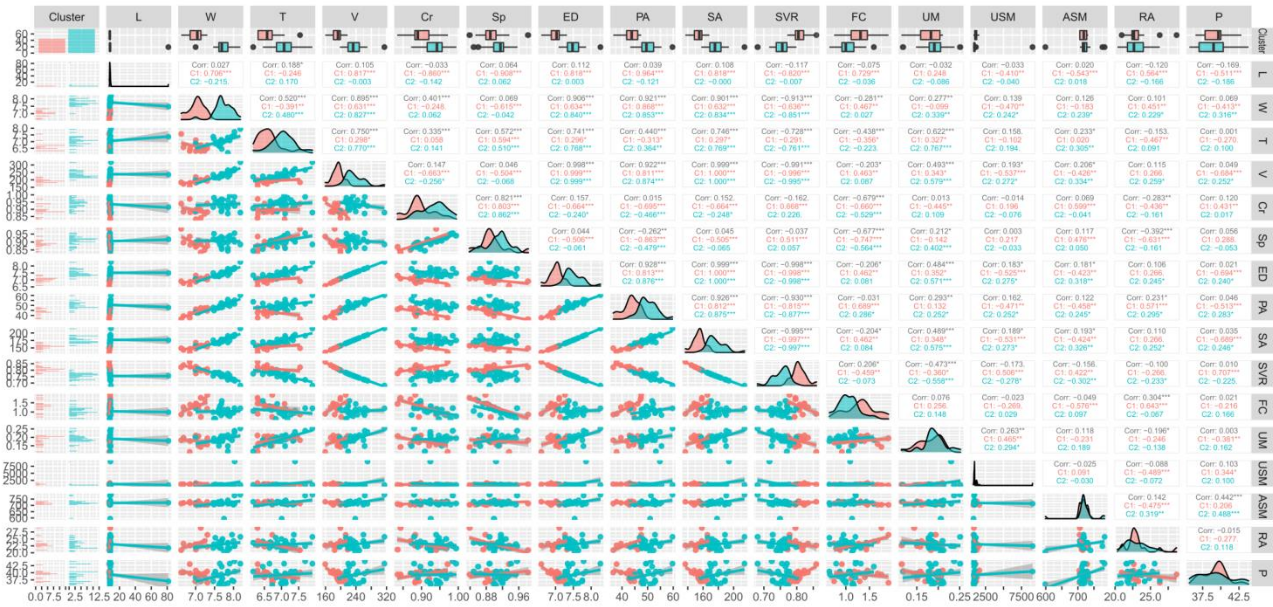

Figure 3. Scatterplot containing Pearson's correlations between physical seed properties. Volume (*V*, mm^3), length (*L*, mm), width (*W*, mm), thickness (*T*, mm), circularity (*Cr*, mm), sphericity (Sp), equivalent diameter (*ED*, mm), projected area (*PA*, mm^2), surface area (*SA*, mm), surface-to-volume ratio (*SVR*), friction coefficient (*FC*), unit mass (*UM*, kg m^{-3}), unit specific mass (*USM*, kg m^{-3}), apparent specific mass (*ASM*, kg m^{-3}), rest angle (*RA*, °), and porosity (*P*, %), evaluated in 40 soybean cultivars.

Discussion

Owing to technological advances in genetic breeding and the production of different soybean seed cultivars, high variations exist in the physical characteristics of soybean seed lots. For higher operational yield in the post-harvest units, reduction of losses and gains in quality, the development of equipment that is flexible in terms of regulations and controls and considers groups of cultivar seeds similar in physical properties is necessary. However, in Brazil, the beneficiation and storage practices of soybean seeds still do not consider the heterogeneity of the seeds, which exist owing to the differences between cultivars. Given this reality, soybean cultivars similar in terms of physical properties need to be identified, which can help form batch groupings for post-harvest equipment adjustments.

The evaluation of the physical properties facilitated the identification of soybean seed cultivars with similar characteristics (C1 and C2) for obtaining more homogeneous seed lots for the pre-cleaning, drying, processing, and storage processes. Obtaining homogeneous seed batches with similar physical characteristics can contribute to the adjustment of each piece of equipment in each post-harvest process and the achievement of better seed quality.

Defining the characteristics of seed similarities enables equipment adjustment according to the seed lots received at the processing unit. Establishing quality control parameters in this manner is highly beneficial for the process. Homogenization of the seed batches handled during receiving, pre-cleaning, drying, processing, and storage minimizes the negative effects of operations on quality. This also allows a storekeeper to seize greater control of the variables in the operations, including flow, flow rate, seed mass, velocity, temperature, air pressure passing through the seed mass, and the dimensions, capacities, and adjustments of the equipments (Payman et al., 2011; Mir et al., 2013).

The identification of cultivars with similar physical seed properties contributes to increased efficiency in sizing, regulation, and maintenance of post-harvest equipment (Mohsenin, 1986, Mao et al., 2020). The clustering of cultivars according to physical seed characteristics allows control over the inclination and dimensions of the equipment during reception, transport, pre-cleaning, and processing; flow and air temperatures during drying; and aeration or cooling of seed mass during storage (Deshpande, Bal, & Ojha, 1993; Bande, Adam, Azni, & Jamarei, 2012; Mao et al., 2020). Homogenizing seed lots according to the properties of the cultivars improves the efficiency of drying systems and the quality of the seeds. It reduces the water content to levels that allow the conservation of water quality during storage (Deshpande et al., 1993; Bande et al., 2012; Jan, Panesar, & Singh, 2019).

Furthermore, knowing the physical properties of the lots from various cultivars facilitates the regulation of ventilation and cooling equipment used for reducing the temperature of the seed mass during storage and minimizing the changes in humidity. During storage, it helps in suppressing the respiratory processes that consumes nutritive reserves of the seeds and the changes linked to the metabolic dynamics that affect germination and vigor (Nori, Moot, & Mills, 2019; Pinheiro, Medeiros, Zavala-León, Dias, & Silva, 2020).

During batch reception, the seed-flow in a discharge hopper is gravity-based, and the inclination angle of the inner walls of the hopper is higher than the rest angle of the seeds. The sphericity, diameter, projected area, surface area, SVR, coefficient of friction, volume variability, and specific seed mass all affect the static capacity of the hopper. While handling and moving the seed mass using bucket elevators, conveyor belts, and threads, the mechanical damage inflicted to the seeds and the carrying capacity depend on adjustments, including those made according to the physical properties of the seeds. Such adjustments are often based on apparent specific mass, sphericity, projected area, surface area, SVR, coefficient of friction, and angle of repose of the seeds (Bande et al., 2012; Nori et al., 2019).

During a pre-cleaning operation, technicians separate impurities and foreign matter from the seed mass using air handling machines and sieves of different holes that are adjusted according to roundness, sphericity, equivalent diameter, and volume (length, width, and seed thickness) for smooth seed-mass flow and cleanliness (Moreano et al., 2018; Mao et al., 2020).

Drying alters the physical characteristics of the seeds. Thus, homogenization of seed lots by physical properties contributes to greater efficiency and uniformity in seed quality during the drying process. To make harvested seeds with high moisture content, usually in the range of 18-22%, more suitable for storage, they are subjected to artificial drying to reduce seed moisture to approximately 12% (w.b.). However, reducing the moisture content of seeds requires heat and mass transfer, which can substantially change the quality and physical properties of the seeds, depending on the method and drying conditions (Coradi et al., 2020b; Guilherme & Nicolin, 2020).

Drying causes changes in seed dimensions, especially a reduction in volume, which additionally alters the circularity, sphericity, equivalent diameter, volume, and specific mass of the seeds (Jung & Yoon, 2018). These changes result from the reduction in the tension inside the cells owing to the removal of water. Volumetric changes are the primary stimuli that cause changes in the physical properties of seeds, which determine the size and shape of the sieve holes used during the processing of agricultural products after harvest (Mao et al., 2020). The separation of soybean-cultivar seed lots into groups (C1 and C2) based on similar physical characteristics can reduce the effects of the drying processes, especially the effect of the drying-air temperature on seed quality.

The goal is to classify lots by size to improve quality and establish seed standards (Coradi et al., 2020b; Mao et al., 2020). Beneficiation is a fundamental operation in seed production programs and improves seed quality by providing conditions for use and meeting the minimum marketing standards established by legal norms (Oliveira et al., 2021). During processing, the seeds undergo several stages; however, not all lots follow the same sequence. This means that the operations in this process depend on the species, cultivars, and physical characteristics of the seeds (Jha & Kachru, 1998). The size and selection of the equipment for processing seeds are based on the physical characterization of the seeds. The flow during beneficiation is a time-consuming process and commonly results in mechanical injuries caused by physical agents during handling, which causes direct damage and render the seeds susceptible to contamination by highly deleterious pathogens (Ixtaina, Nolasco, & Tomas, 2008; Oksanen, 2018).

For seed processing, characterizing the seed lots (C1 and C2) according to the cultivar and its physical properties is essential, with emphasis on circularity, sphericity, volume, and specific mass. The quality of seeds is directly associated with the removal of inert material, seeds of weeds and other crops, and seeds of other cultivars, which depends on the proper selection of cleaning and separation equipment, the arrangement of the machines in the seed processing unit, and standardization of the physical seed properties (Sirisomboon, Kitchaiya, & Pholpho, 2007; Payman et al., 2011). A densimetric table is used to improve the physical quality of soybean seed lots by increasing the specific mass. It typically separates seeds based on the mass of one-thousand seeds (Atungulu & Olatunde, 2021). In a study conducted by Bakhtavar, Afzal, and Basra (2019), which aimed to evaluate the evolution of the physical characteristics (degree of humidity, percentage of impurity, apparent specific mass, and one-thousand seed mass) of the seeds of several soybean cultivars along the processing line, the authors concluded that processing reduces the impurities in many soybean seeds. The processing step is mainly conducted using a cleaning machine and completed using a densimetric table.

Atungulu and Olatunde (2021) reported that even with all the technologies available during the reception, pre-cleaning, and processing steps, qualitative and quantitative losses originate during storage when a seed mass is constantly subjected to external factors, such as temperature and relative humidity; chemical factors, such as the presence of oxygen; and biological factors, such as the development of bacteria and fungi (Khomari, Golshan-Doust, Seyed-Sharifi, & Davari, 2018). Therefore, minimizing such losses due to seed heterogeneity in the stages before the storage process is essential for increasing the efficiency and consequent profitability of the soybean seed production process (Homer, Patala, & Priedeman, 2015; Coradi et al., 2020b).

Conclusion

We obtained two groups of soybean seed cultivars with each group exhibiting similar physical characteristics. The USM was the physical property that contributed the most to the formation of C1, whereas the other physical properties contributed to the formation of C2. The soybean cultivars comprising C1 were similar to each other only with respect to USM. In contrast, the cultivars allocated to group C2 were more similar according to all the other properties evaluated. This is the first study in which cultivars were clustered based on the main physical properties of soybean seeds and the cultivars with the highest uniformity for the properties assessed were identified. We recommend these results for the development and adjustment of equipment for seed processing. Furthermore, these results can be used as guidelines to selection the genotypes for the genetic improvement of soybean to minimize variations in the physical characteristics of the seeds and obtain greater efficiency in soybean-seed processing stages.

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