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Seed Technology/ Original Article

Packaging of soybean seeds stored in different environments

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Abstract – The objective of this work was to evaluate packaging for preserving the quality of soybean (*Glycine max*) seeds stored in different environments. The experiment design was completely randomized, in a factorial arrangment with six seed storage conditions: natural atmosphere (NA), laminated packaging atmosphere (LPA), modified atmosphere in polyethylene packaging (MAPP), refrigerated atmosphere in raffia packaging (RARP), refrigerated atmosphere in laminated packaging (RALP), and modified and refrigerated atmosphere in polyethylene packaging (MRAPP), with four storage times (zero, two, four, and six months). Storage time reduces the quality of soybean seeds after two months in all tested packaging. The germination of the soybean seeds was maintained in the following packaging: LPA, RARP, RALP, and MRAPP. LPA is the most efficient packaging for soybean seeds, which show the highest percentage of germination for the longest storage time, without requiring any modification or refrigeration of the atmospheric storage environment.

Index terms: chilled atmosphere, coated bags, equilibrium moisture content, modified atmosphere in bags, sensor applications in bag.

Embalagens de sementes de soja armazenadas em diferentes ambientes

Resumo – O objetivo deste trabalho foi avaliar embalagens para a conservação da qualidade de sementes de soja (*Glycine max*) estocadas em diferentes ambientes. O delineamento experimental foi inteiramente casualizado, em arranjo fatorial com seis condições de armazenamento de sementes: atmosfera natural (NA), atmosfera de embalagem laminada (LPA), atmosfera modificada em embalagem de polietileno (MAPP), atmosfera refrigerada em embalagem de ráfia (RARP), atmosfera refrigerada em embalagem laminada (RALP), e atmosfera modificada e refrigerada em embalagem de polietileno (MRAPP), com quatro tempos de armazenamento (zero, dois, quatro e seis meses). O tempo de armazenamento reduz a qualidade das sementes de soja após dois meses em todas as embalagens testadas. A germinação das sementes de soja foi mantida nas seguintes embalagens: LPA, RARP, RALP e MRAPP. A LPA é a embalagem mais eficiente para as sementes de soja, que apresentam maior percentual de germinação pelo maior tempo de armazenamento, sem necessitar de modificação e/ou refrigeração do ambiente de armazenamento.

Termos para indexação: atmosfera refrigerada, bolsas revestidas, umidade de equilíbrio higroscópico, atmosfera modificada em bolsas, aplicações de sensores em bolsas.

Introduction

After production, soybean seeds are subjected to post-harvest operations for cleaning, drying, processing, and storing them (Lutz et al., 2022), during which, in the processing units, the seeds can be artificially cooled for better conservation (Coradi et al., 2022). After some time, the seeds are often transported over long distances in uncontrolled environments and pre-stored before sowing in sheds or spaces without temperature control, losing their germination viability (Müller et al., 2020). In addition, the use of permeable packaging can favor intergranular gas exchange with the environment (Rahman & Cho, 2016), accelerating metabolic processes and, consequently, interfering in the equilibrium moisture content and seed germination (Nambara et al., 2010).

Evaluating different types of packaging technologies for seed storage, Odjo et al. (2022) evaluated hermetic storage technologies to preserve maize seed quality and minimize grain quality loss. According to the authors, the type of storage technology causes less harm for seed germination at locations over 2,000 m above sea level and affects more at sites under 500 m above sea level. On average, the germination capacity of seed stored using non-hermetic technologies, it is polypropylene bags with or without insecticide or lime, dropped 56.0% at lowland sites, whereas for seed stored using hermetic metal silos or hermetic bags it dropped 2.8%.

Seifu et al. (2023) compared two hermetic bags (super grain pro bag and purdue improved crop storage bag) with three non-hermetic bags (woven polypropylene bag lined with polyethylene, polypropylene bags, and jute bags) for the storage of faba bean seeds for 24 months. The authors verified that the hermetic bags maintained germination percentage above 90% during 12 months of storage. The vigor index remained above 1,600 mg% for hermetic bags; however, non-hermetic bags exhibited a rapid drop in vigor index at six months of storage.

Controlling the storage environment can be an alternative (André et al., 2022) to unfavorable climate diversities that may occur when storing soybean seeds in different producing regions (Lutz & Coradi, 2022). For this purpose, it is used packaging with suitable porosity and material that can minimize gas exchange during packaging and extend the storage time and conservation of seed quality until sowing.

On a commercial scale, soybean seeds are stored and transported from processing units to rural producers in packages known as big bags (Chirchir et al., 2017), which are large and flexible packages, made of polypropylene and highly resistant to tearing (Baributsa & Baoua, 2022). However, the big bags are packages that allow gas exchange between the intergranular air and the ambient air (Rahman & Cho, 2016).

Zuchi et al. (2013) investigated the effects on physiological quality of soybean seed stored in refrigerated environments with porosity packaging. The authors verified that the moisture content of the soybean seeds evaporated during the storage time due to the influence of the relative humidity of the air when there was an increase in the moisture content up to 60 days of storage, and then there was a reduction in humidity until the end of 120 days of storage.

However, Smaniotto et al. (2014), evaluating the storage of soybean seeds with an average temperature of 27°C during 180 days of storage, observed a reduction in the moisture content due to the permeability of the packaging. Kuyu et al. (2022) evaluated the maintenance of seed quality with different grain storage technologies with potential different hermetic storage technologies, such as PICS bags, metal silos and polypropylene bags plus low-density polyethylene bags, and conventional jute sacks and polypropylene bags, and the authors found that, of all storage methods, metal silos and PICS bags were the most effective at preserving seed quality.

The objective of this work was to evaluate packaging for preserving the quality of soybean seeds stored in different environments.

Materials and Methods

The Intacta RR2 Pro soybean (*Glycine max* L.) seeds (Bayer, São Paulo, SP, Brazil) were obtained in a processing and storage unit, and the seeds were cleaned and dried in drying silos with radial air flow at a temperature of 40°C up to 12% wet basis of moisture content. The experiment with seeds storage was characterized by a completely randomized design, in a 6x4 factorial scheme, being six seed storage conditions: natural atmosphere (NA), laminated packaging atmosphere (LPA), modified atmosphere in polyethylene packaging (MAPP), refrigerated atmosphere in raffia packaging (RARP), refrigerated atmosphere in laminated packaging (RALP), and modified and refrigerated atmosphere in polyethylene packaging (MRAPP), with four storage times: zero, two, four, and six months. Three replicates were performed for each treatment.

The packaging was made of raffia, laminated materials, and polyethylene, with dimensions of 20 cm (wide) x 30 cm (height) (Videplast Company, Videira, SC, Brazil). The plastic polyethylene packaging was 0.075 mm thick, the raffia one was 0.250 mm thick, and the laminated one had a 0.075 mm thick polythene layer and a 0.175 mm thick laminate layer.

Laminated materials are made of braided polypropylene and is laminated with polyethylene film, coated with a volatile multimetal corrosion inhibitor, resistant to a high tensile strength of $9.8x10^5$ N m^{-2} and 20% longitudinal elongation. The polyethylene packaging was constituted by partially crystalline and flexible thermoplastic resin material, obtained through the ethylene polymerization. It is formed by polar organic compounds that can change according to the environment temperature. The laminated packaging was characterized as aseptic, with thick walls of a polyethylene layer, polypropylene layer, and laminated layer, with resistance to perforation of 4.5 MPa, 1’ valve of flexible polyethylene plastic material for filling.

Over the six months of storage of the soybean seeds, the ambient storage variations of temperature and relative humidity (Figure 1), as well as the seed mass temperature were monitored by a prototype (Figure 2) of an embedded system composed of an ESP8266 microcontroller (Espressif Systems, Shanghai, China), a DHT22/AM2302 temperature and relative humidity sensor (Aosong Electronics, Guangzhou, China), an independent system with a source power supply, and a wireless communication

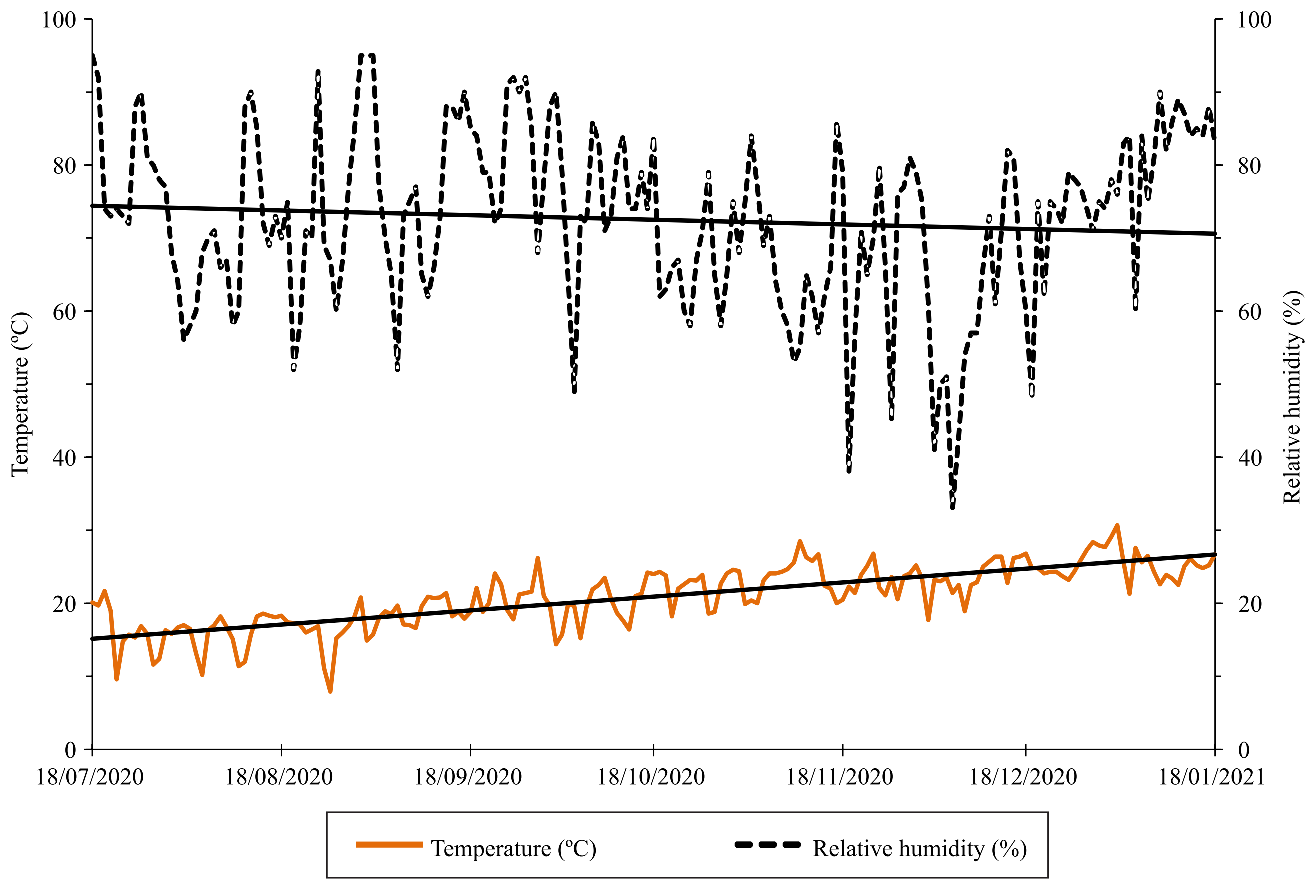

Figure 1. Monitoring the temperature and relative humidity of the natural storage environment of soybeans (*Glycine max*) seeds.

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device as hardware components (Figure 2) (Lutz et al., 2022). The prototype programming was conducted on Arduino IDE software open-source version 1.8.15 (Arduino IDE, 2021), a platform developed during the experiment. The prototype was developed to mesure temperature and relative humidity of the intergranular air daily in every 5 min.

The receipt of data collected by the sensors was achieved through a Thing Speak platform and Open Source for Internet of Things (IoT) application (Figure 2) and allows the transference of the sensor data through HTTP/HTTPS and MQTT protocols, providing a real-time interface. Figure 2 C shows the operating structure of the platform, allowing the abstraction of the infrastructure resources necessary to implement the IoT solution.

The equilibrium moisture content of the stored seed mass was calculated by Chung-Pfost modified equation:

$$EMC = \frac{-1}{c}\ln\left(-\left(\frac{T+b}{a}\right)\ln(RH)\right)$$

where, EMC is the equilibrium moisture content (%); RH is the relative humidity (decimal); T is the temperature (°C); a, b, and c are the soybean parameters (a = 360, b = 75, c = 0.183).

The characterization of ambient and refrigerated air and intergranular air in the storage of soybean seeds were calculated by the following four equations:

$$P_{sat} = 6.107 \times 10^{\left(\frac{7.5T}{237.3+T}\right)},$$

where, P_{sat} is the saturation vapor pressure (kPa); and T is the temperature (°C).

$P_v = RH \times P_{sat}$, where, P_v is the partial air pressure (kPa); and RH is the relative humidity (decimal).

$w = 0.622(P_v / P_{atm} - P_v)$, where, w is the moisture ratio (kg water vapor kg^{-1} dry air); and P_{atm} is the atmospheric pressure (101 kPa).

$h = 1.006(T - 273.15) + w(2501 + 1.775(T - 273.15))$, where, h is the enthalpy (kJ kg^{-1} of dry air); and T is the temperaturee (K).

To assess the physiological quality of the seeds, 36 samples of each treatment and storage condition were collected every two months. The moisture content of the seeds was determined with the aid of an indirect meter by electrical capacitance, model G1000 (Gehaka, São Paulo, SP, Brazil) in three replicates (Brasil, 2013). The electrical conductivity and germination test evaluation were performed according to the criteria established for seed analysis (Brasil, 2009).

The results obtained were analyzed statistically by the computer program Sisvar, version 4.0, by the Tukey's test, at 5% probability (Ferreira, 2019). To verify the interrelationship between the variables and the treatment of each experiment, the data were subjected to principal component analysis. A biplot was built with the first two main components to facilitate the interpretation of the results. In this biplot, clusters were defined to use the k-mean algorithm, which groups the treatments whose centroids are closest until there is no significant variation in the minimum distance of each observation to each centroid (Naldi

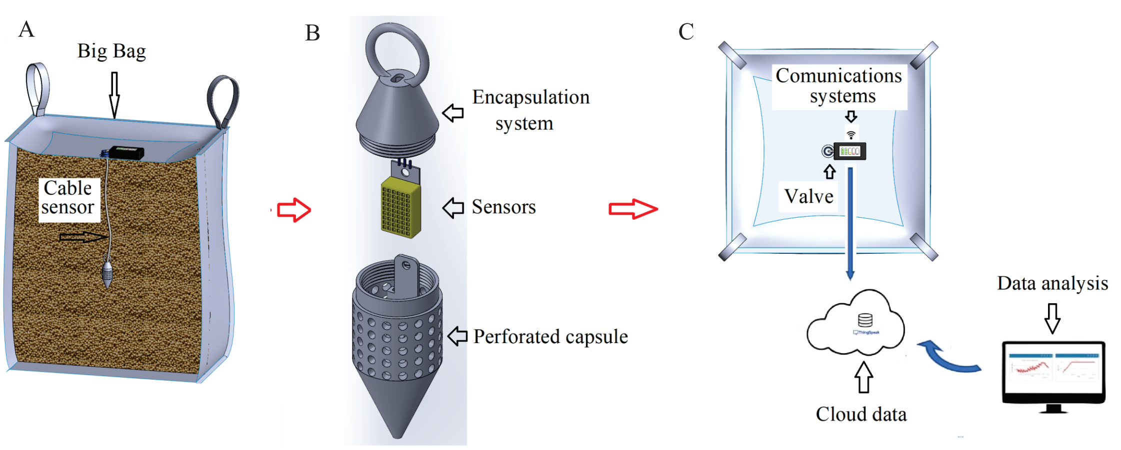

Figure 2. Prototype bag and cable-sensor (A), sensor encapsulation system (B) for measuring the intergranular temperature and relative humidity of soybean (*Glycine max*) seeds stored in bags (C).

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et al., 2011). Subsequently, the Pearson correlation coefficients were estimated to verify the association between variables in the processing conditions. These analyzes were performed with the aid of the ggfortify package of the free application R (Tang et al., 2016) and followed the procedures recommended by Naldi et al. (2011).

Results and Discussion

The intensities of gas exchanges between the storage ambient and the intergranular air of the stored seeds varied with the storage conditions and the permeability of the packages (Table 1). The temperature and relative humidity of the air provided variations in the psychrometric properties, such as the enthalpy and the moisture ratio, as well as the moisture content and equilibrium moisture content of the seeds. In LPA, RARP, RALP, and MRAPP the soybean seeds had variations in equilibrium moisture content by up to 1%, remaining the hygroscopic balance over the storage time, while in NA and MAPP storage conditions there was an increase in equilibrium moisture content in the seeds up to 4%.

It was observed that NA and MAPP presented the highest moisture ratios increasing over the storage time, and LPA, RALP, RARP, and MRAPP had the lowest moisture ratios. The enthalpy variable had the same behavior as the moisture ratio. The results indicated that storage in NA and MAPP allowed mass and energy exchange between the stored seeds and the environment, reducing seed quality, while LPA and RALP, RARP, and MRAPP stood out for better seed conservation, because laminated packages were composed of a better barrier structure with three layers: polyethylene, polypropylene and polyester (Andreasson et al., 2014). These results are in accordance with

Table 1. Monitoring of the atmospheric conditions of the intergranular storage air in soybean (*Glycine max*) seed packages.

CA	Storage time (months)	Temperature (°C)	RH (%)	EMC (%)	P_{sat} (kPa)	P_v (kPa)	W (kg water vapor kg^{-1} dry air)	H (kJ)
NA(2)	0	16.71±3.4	57.89±3.9	12.31±0.9	1.90	1.08	0.00675	33.89
NA	2	16.71±3.3	57.65±5.2	12.33±1.0	1.90	1.08	0.00675	33.89
NA	4	25.10±3.5	55.54±4.8	14.20±0.9	3.17	1.74	0.01092	49.96
NA	6	27.31±3.0	46.65±5.1	16.15±0.8	3.57	1.64	0.01027	50.57
LPA	0	16.71±3.8	59.66±5.4	11.96±0.4	1.90	1.12	0.00699	34.50
LPA	2	16.71±3.2	59.92±4.3	11.82±0.4	1.90	1.12	0.00699	34.50
LPA	4	20.10±3.5	68.31±5.2	11.22±0.4	2.34	1.59	0.00995	47.50
LPA	6	20.31±3.2	65.69±4.1	12.88±0.3	2.34	1.52	0.00950	48.63
MAPP	0	16.71±3.1	59.66±4.7	11.94±0.6	1.90	1.12	0.00699	34.50
MAPP	2	16.71±3.4	55.27±4.3	12.64±0.4	1.90	1.05	0.00651	33.29
MAPP	4	24.10±3.3	55.52±4.9	14.16±0.5	2.98	1.64	0.01027	48.33
MAPP	6	24.31±3.6	54.83±5.2	14.84±0.5	3.04	1.64	0.01028	50.60
RARP	0	15.00±2.0	57.89±5.0	11.73±0.5	1.71	0.97	0.00604	30.37
RARP	2	15.00±2.0	52.86±4.3	12.71±0.4	1.71	0.89	0.00551	29.02
RARP	4	15.00±2.0	52.72±4.6	12.55±0.5	1.71	0.89	0.00551	29.02
RARP	6	15.00±2.0	51.09±4.7	12.71±0.4	1.71	0.87	0.00540	28.74
RALP	0	15.00±2.0	59.66±4.0	11.38±0.3	1.71	1.01	0.00626	30.91
RALP	2	15.00±2.0	55.00±3.9	12.06±0.5	1.71	0.94	0.00583	29.83
RALP	4	15.00±2.0	56.48±5.5	12.93±0.6	1.71	0.95	0.00594	30.10
RALP	6	15.00±2.0	55.65±5.1	11.90±0.5	1.71	0.94	0.00583	29.83
MRAPP	0	15.00±2.0	57.89±3.9	11.73±0.6	1.71	0.97	0.00604	30.37
MRAPP	2	15.00±2.0	53.53±4.0	12.39±0.3	1.71	0.90	0.00562	29.29
MRAPP	4	15.00±2.0	61.20±4.2	11.02±0.4	1.71	1.04	0.00647	31.45
MRAPP	6	15.00±2.0	51.91±4.8	12.71±0.5	1.71	0.87	0.00540	28.74

(1)RH, relative humidity; EMC, equilibrium moisture content; Psat, saturation vapor pressure; P_V, partial vapor pressure; W, moisture ratio; H, enthalpy. (2)NA, natural atmosphere; LPA, laminated packaging atmosphere; MAPP, modified atmosphere in polyethylene packaging; RARP, refrigerated atmosphere in raffia packaging; RALP, refrigerated atmosphere in laminated packaging; MRAPP, modified and refrigerated atmosphere in polyethylene packaging

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Kalsa et al. (2019), that studied different postharvest preservation strategies for stored wheat seeds. The results indicated that storage strategies maintained the seed quality compared to the control treatment.

The interactions between the storage time and storage condition factors were significant (Table 2). The permeability of the NA and MAPP allowed greater gas exchange and, consequently, changes in the moisture content of the seeds after two months of storage, while the LPA, RARP, RALP, MAPP, and MRAPP packaging kept the seeds in equilibrium moisture content with moisture close to the established conditions of 12% w.b. of storage (Table 2), with changes up to 13% w.b. only after four months of storage.

The combination of packaging and the storage conditions showed advantages for the conservation of seed germination (Table 2). The LPA, RARP, RALP, and MRAPP presented the higher percentage variation of germination after 6 months. Some authors verified in soybean seeds stored under uncontrolled humidity and temperature conditions an increase in moisture content at 45 and 180 days (André et al., 2022); however, moisture content fluctuation occurred between 90 and 135 days due to the variation in relative humidity of the air, which favored the sorption processes of the seeds (Ali et al., 2020; Coradi et al., 2022). Evaluating different seed packaging materials for quality of rice seed stored at different periods of time, Assaye et al. (2023) found high germination, seedling length, seedling dry weight, and vigor indices due to the low variation in the water content of seeds over storage time, similar to the results obtained with LPA, RARP, RALP, and MRAPP packaging.

The soybean seeds stored in NA and MAPP packaging, which presented greater permeability, allowed exchange with greater humidity intensity between the ambient air and the intergranular air, increasing the equilibrium moisture content during storage. Virgolino et al. (2016) observed a greater conservation of moisture contents and temperature in soybean seed lots stored in polyethylene big bags with

Table 2. Evaluation of soybean (*Glycine max*) seed quality according to storage conditions and time[(1)].

Storage conditions	Months			
	0	2	4	6
	Moisture content (% w.b.)			
NA[(2)]	12.17Ad	14.22Ac	15.87Ab	16.62Aa
LPA	12.17Aa	12.35Ba	12.27Aa	12.10Aa
MAPP	12.17Ac	12.30Bc	13.45Bb	14.25Ba
RARP	12.17Ab	12.17Bb	12.15Cb	13.17Ca
RALP	12.17Ab	12.22Bb	12.20Cb	13.90Ca
MRAPP	12.17Ab	12.35Bb	12.82Cb	13.35Ca
	Electric conductivity (μS cm^{-1} g^{-1})			
NA	142.10Ad	196.23Ac	220.24Ab	242.45Aa
LPA	142.10Ac	152.45Cb	175.56Ba	176.37Ca
MAPP	142.10Ac	155.34Cc	172.20Bb	206.45Ba
RARP	142.10Ad	156.23Cc	167.18Cb	178.89Ca
RALP	142.10Ac	164.15Bb	167.34Cb	178.65Ca
MRAPP	142.10Ad	155.34Cc	170.65Bb	179.32Ca
	Germination (%)			
NA	100.00Aa	95.00Bb	92.00Cc	85.00Dd
LPA	100.00Aa	100.00Aa	99.00Aa	98.50Ab
MAPP	100.00Aa	94.00Ba	93.00Cb	87.50Cc
RARP	100.00Aa	99.50Aa	98.50Ab	98.50Ab
RALP	100.00Aa	99.50Aa	98.50Ab	98.50Ab
MRAPP	100.00Aa	99.00Aa	97.00Bb	97.25Bb

[(1)]Values followed by equal letters, in the row, do not differ from each other by Tukey's test, at 5% probability. [(2)]NA, natural atmosphere; LPA, laminated packaging atmosphere; MAPP, modified atmosphere in polyethylene packaging; RARP, refrigerated atmosphere in raffia packaging; RALP, refrigerated atmosphere in laminated packaging; MRAPP, modified and refrigerated atmosphere in polyethylene packaging.

low permeability. Baributsa & Baoua (2022) observed a significant reduction in moisture content due to the permeability of the packaging that allowed the seeds to enter hygroscopic balance with high relative humidity of the air.

The electrical conductivity test for seed quality showed that the storage time influenced the increase in amount of leached ions from the soybean seeds, regardless of the storage condition (Table 2) or type of packaging, except for NA after six months stored. After six months of storage, NA and MAPP had the highest values of electrical conductivity, while LPA, RALP RARP, and MRAPP had the lowest values, not differing from each other.

The results obtained for the germination of soybean seeds under LPA, RARP, RALP, and MRAPP conditions were close to the ones found by Zuchi et al. (2013) and Smaniotto et al. (2014). The authors verified alterations on the physiological quality of soybean seeds in refrigerate (Zuchi et al., 2013) and natural environments (Smaniotto et al., 2014). The germination percentage of soybean seeds reduced over the storage time in the NA, 85%, and MAPP, 87%, packaging, the opposite of what occurred for the LPA, RALP, RARP, and MRAPP packaging, which remained between 97 to 98%.

The results can be better observed in the dispersion between the variables and their Pearson correlations (Figure 3 A). According to the storage conditions, there was a strong negative correlation between germination and electrical conductivity, besides a weak negative correlation between the variables moisture and electrical conductivity, and a weak positive correlation between the variables moisture content and germination. The results indicated that the increase in electrical conductivity increased the deterioration process of the seeds, reducing the germination percentage in NA and MAPP packaging, while the increase in moisture contents caused an acceleration of the metabolic activity and respiration of the seeds, increasing cellular tissue damage.

The analysis of the main components brought together 95.7% of the total variation between treatments (Figure 3 B). The vectors pointed to the variables that

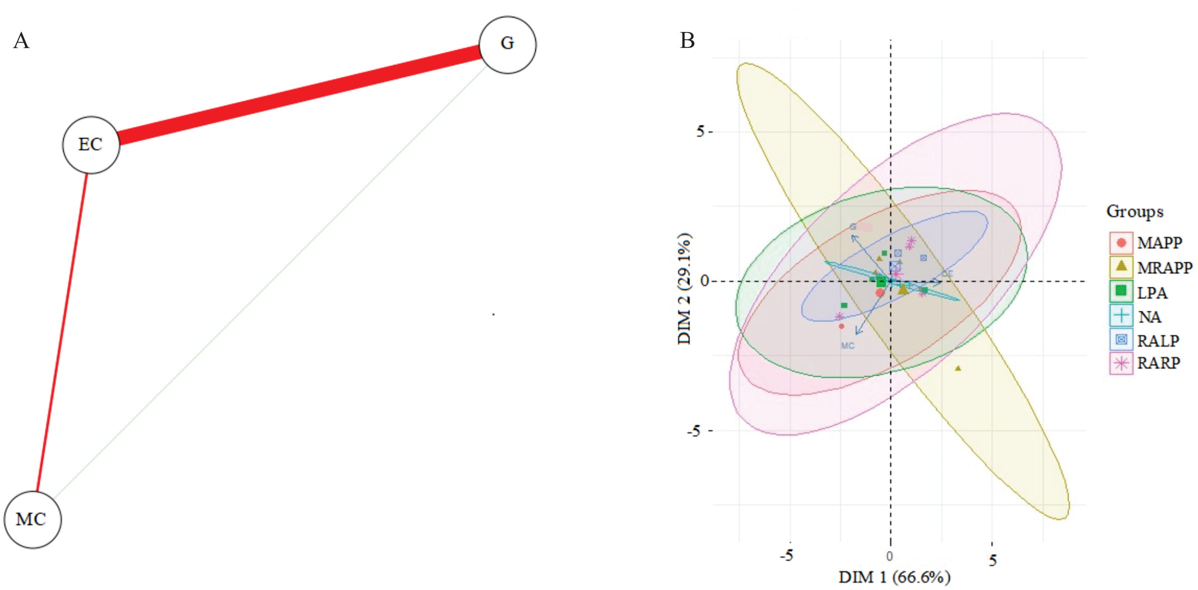

Figure 3. Scatterplot containing Pearson and dispersion between moisture content variables (MC), electric conductivity (EC), and germination (G) evaluated in soybean (*Glycine max*) seeds stored under different conditions. The green lines link variables with positive correlation and the red lines have negatively correlated variables. The thickness of the line is proportional to the magnitude of the correlation (A). Principal component analysis for the moisture content (MC), electric conductivity (EC), and germination (G) evaluated in soybean seeds stored under different conditions (B).

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most influenced the similarity of treatments, showing that, at four and six months of storage, NA and LPA obtained similar results for the electrical conductivity test in soybean seeds. At two, four, and six months of storage, LPA, RALP, and MRAPP packages obtained similar results for the germination of seeds, opposite to the results of the electrical conductivity test.

The NA and MAPP packaging resulted in high levels of leaching and changes in the cellular structure of the seeds. The results obtained are according to McGilp et al. (2020) when evaluating the quality of soybean seeds stored in multifoliate paper, big bags, and polypropylene packaging. The authors verified an increase in electrical conductivity due to the release of exudates, indicating greater deterioration of the seeds over the storage time.

The LPA, RALP, RARP, and MRAPP packaging maintained stability of the storage environment, moisture content, and germination potential of the seeds until the end of the storage time, but it was observed a gradual increase in the electrical conductivity after two months of storage. Smaniotto et al. (2014), studying the physiological quality of stored soybean seeds, found that soybean seeds with moisture contents of 12 to 14% w.b., artificially refrigerated at 20°C, maintained the germination percentage of the seeds for over six months of storage. In addition, Zuchi et al. (2013) found beneficial effects of refrigeration when they evaluated the germination of soybean seeds stored under different conditions. The results obtained by Zuchi et al. (2013) and Smaniotto et al. (2014) were similar to those obtained in this study with RARP packaging.

Although in this study the polyethylene and MRAPP, RARP, and RALP polypropylene packaging have shown good results of germination, the LPA packaging maintained the highest germination percentages since the first months of storage without modifying or refrigerating atmospheric storage environment. For this reason, LPA stood out in seed quality, being considered the best packaging for storage of soybeans in relation to the other technologies tested.

Conclusions

1. The storage time reduces the quality of soybean (*Glycine max*) seeds after two months for all tested packaging.

2. The germination of the soybean seeds is maintained in the following packaging: Laminated Packaging Atmosphere (LPA), Refrigerated Atmosphere in Raffia Packaging (RARP), Refrigerated Atmosphere in Laminated Packaging (RALP), and Modified and Refrigerated Atmosphere in Polyethylene Packaging (MRAPP).

3. Laminated Packaging Atmosphere (LPA) stands out as an efficient one for soybean seeds, because it presents the highest percentage of seed germination for the longest storage time, not requiring modification or refrigeration of the atmospheric storage environment.

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