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Original Article

Traceability of soybean seed quality before and after transport under different conditions[1]

Rastreabilidade da qualidade de sementes de soja antes e após o transporte em diferentes condições

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HIGHLIGHTS:

Transport distance and time significantly influenced soybean seed physiological performance during logistics operations.
Thermal tarpaulins combined with shorter routes maintained seed vigor compared to conventional coverings.
Digital sensors enabled real-time monitoring, revealing temperature variations affecting seed membrane integrity.

ABSTRACT: The quality of soybean seeds is crucial for production efficiency, while adverse conditions, such as temperature and humidity variations during transport, can compromise this quality and negatively affect seed performance. Therefore, the objective was to evaluate the physiological quality of the seeds by monitoring the internal and external conditions of temperature and relative humidity of the seed mass using digital sensors during transport. Seeds of the Bônus IPRO cultivar were evaluated before and after transportation. This experiment was conducted in a completely randomized design, with seven treatments, one of which was a control treatment, corresponding to seeds before transport, and the other six obtained by combining the types of tarpaulin and routes (WT×CAT, NT×CAT, WT×RON, NT×RON, WT×VR and NT×VR) in four replicates. Evaluations were performed for moisture content, accelerated aging, germination, normal seedlings, abnormal seedlings, ungerminated seeds, tetrazolium, emergence, electrical conductivity, dry mass, and seedling length. The data were analyzed by analysis of variance, Dunnett's test, and Pearson's correlation ($p \leq 0.05$). Routes longer than 1,000 km resulted in reduced seed vigor and viability, but remained within commercial standards. Thermal tarps reduced external variation by about 11 °C, although the internal temperature of the seeds remained stable, while digital sensors effectively monitored the entire process. All lots maintained germination ≥ 90%, indicating that current logistics practices are adequate for short-term transport.

Key words: *Glycine max* (L.) Merr., physiological quality, temperature, relative humidity

RESUMO: A qualidade das sementes de soja é crucial para eficiência produtiva, enquanto que as condições adversas, como as variações de temperatura e umidade durante o transporte, podem comprometer essa qualidade e afetar negativamente o desempenho das sementes. Sendo assim, objetivou-se avaliar a qualidade fisiológica das sementes, monitorando as condições internas e externas de temperatura e umidade relativa da massa de sementes, por meio de sensores digitais durante o transporte. As sementes da cultivar Bônus IPRO foram avaliadas antes e após o transporte. Assim, este experimento foi conduzido em delineamento inteiramente casualizado, com sete tratamentos, sendo um tratamento controle, correspondente às sementes antes do transporte, e os outros seis obtidos pela combinação dos tipos de lona e rotas de transporte (LB×CAT, LN×CAT, LB×RON, LN×RON, LB×VR e LN×VR) em quatro repetições. Foram realizadas avaliações de teor de água, envelhecimento acelerado, germinação, plântulas normais, anormais, sementes não germinadas, tetrazólio, emergência, condutividade elétrica, massa seca e comprimento de plântulas. Os dados foram analisados usando análise de variância, teste de Dunnett e correlação de Pearson ($p \leq 0{,}05$). Rotas superiores a 1,000 km resultaram em redução do vigor e da viabilidade das sementes, mas ficaram dentro de padrões comerciais. Em relação as lonas térmicas, elas reduziram a variação externa em cerca de 11 °C, embora a temperatura interna das sementes tenha se mantido estável, enquanto que os sensores digitais monitoraram com eficácia todo o processo. Todos os lotes mantiveram germinação ≥ 90%, indicando que as práticas logísticas atuais são adequadas para transporte de curto prazo.

Palavras-chave: *Glycine max* (L.) Merr., qualidade fisiológica, temperatura, umidade relativa

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Introduction

Soybean cultivation is the main commodity of Brazilian agribusiness, with soybean production in the 2024/2025 harvest reaching more than 169.5 million tons, representing an increase of 14.7% over the 2023/2024 harvest and surpassing the previous record set in the 2022/2023 harvest by 8.8% (CONAB, 2025).

To ensure this production, an efficient seed production system is essential, as seed quality is one of the pillars for crop success, influencing its initial population establishment. High-quality seeds have high germination and vigor, physical and genetic purity, and excellent health (Pereira et al., 2021). Seed vigor in this case tends to be reduced by prolonged storage (Zhao et al., 2021) and is affected by genetic and environmental factors throughout seed development (Dai et al., 2022); this characteristic encompasses germination, emergence, seedling growth (Barik et al., 2022), as well as storage capacity and stress tolerance (Li et al., 2022).

Thus, the quality of soybean seeds is crucial for high productivity, but on a commercial scale, seeds are initially stored and then transported in large bags to rural producers, often under uncontrolled environmental conditions. This exposure during transport can compromise quality, even if the seeds were initially stored under favorable conditions, so it should be highlighted that the recommended parameters include temperatures below 18 °C and relative humidity between 50 and 60% (Zuchi, 2018). In addition, temperature and humidity fluctuations from harvest to sowing are critical concerns that can affect seed quality (Coradi et al., 2020a), and refrigerated environments have been identified as an effective solution to reduce the negative effects on soybean seeds and maintain quality (Ferreira et al., 2017; Coradi et al., 2020a).

To minimize these impacts, some logistics companies offer refrigerated transport, ensuring stable temperature and relative humidity during transport. As an alternative, thermal tarps are also used, which have gained relevance in seed transport to cover trucks, preferably with thermal insulation (Henning et al., 2020). This is crucial because even short-term variations in conditions, high moisture content, relative humidity, and temperature can reduce seed quality (Smaniotto et al., 2014). However, maintaining post-harvest quality and meeting market expectations remains a challenge.

Although several factors affect productivity during crop development, seeds with high vigor have greater potential to withstand adverse environmental conditions (Pereira et al., 2021). Seeds are the fundamental input in agricultural production (Zhai et al., 2020), while vigor is a broad indicator of seed quality, encompassing the intensity of physiological activity and characteristics expressed during germination and emergence, including germination rate, emergence index, seedling development potential, plant resistance, and productive capacity (Zhou et al., 2020).

Given the influence of environmental conditions on seed performance during transport, this study evaluated the impact of logistical and environmental factors on the physiological quality of soybeans using real-time monitoring. It highlights that effective implementation of traceability can add value to products and reduce losses during transport and storage (Finger et al., 2023). The hypothesis is that thermal tarps, combined with shorter transport distances, can mitigate quality loss, preserving vigor and viability until sowing.

Thus, the objective of this study was to evaluate seed quality before and after transport using parameters such as moisture content, germination, normal seedlings, abnormal seedlings, ungerminated seeds, tetrazolium test, emergence, electrical conductivity, dry mass, seedling length, and accelerated aging. Digital sensors were used to record the internal and external temperature and relative humidity of the seed mass, comparing different types of tarpaulins for three logistics routes.

Material and Methods

The work was carried out at the Instituto Federal de Educação, Ciência e Tecnologia, Campus of Rio Verde, Goiás, Brazil (17° 48′ 11.4″ S; 50° 54′ 25.3″ W), in partnership with the company Uniggel Sementes (18° 25′ 59.7″ S; 52° 53′ 9.7″ W), located in the municipality of Chapadão do Céu, Goiás. Both locations are situated in tropical climate regions, according to the Köppen-Geiger classification, characterized by a dry season in winter. The climate in Chapadão do Céu is classified as Aw (tropical savanna), but due to its higher altitude, it can also be described as Cwa (tropical with dry winter at higher altitudes). Rio Verde has an Aw climate (tropical savanna), which, according to the Thornthwaite classification, corresponds to B1 w A′ - a humid megathermal climate with moderate water deficiency during winter. This climate pattern is typical of the Brazilian Cerrado.

The genetic material used in this study was the commercial soybean cultivar BMX Bônus IPRO, which has high vigor (≥ 90% vigor), maturation group of 7.9 (intermediate to late cycle, 105-118 days), indeterminate growth habit, thousand-seed weight of approximately 190 grams, and recommended population of 250 to 300 thousand plants/ha. These characteristics confer good physiological quality, high productive potential, and adequate row closure, and this material was evaluated in September 2023, coinciding with the beginning of its distribution. The seeds were produced under conventional growing conditions during the 2022/2023 season in a commercial multiplication field, with sowing in December 2022 and harvesting in April 2023.

Immediately after harvesting, the seeds were weighed and placed into a hopper and artificially dried at a temperature of 40 °C using continuous flow dryers until they reached a moisture content of 12.00% w.b. During the processing stage, the seeds were pre-cleaned, distributed on sieves to remove impurities and classified into different sizes. They were then sent to the densimetric table, to separate seeds with different bulk densities. Seed processing plays a fundamental role in soybean seed production, encompassing several stages, from seed reception and drying to seed storage.

After processing, the seeds were immediately packaged into big bags with a capacity of 1,000 kg, and stored in a climate-controlled environment monitored by a Kasvi digital thermo-hygrometer, maintained at an average temperature of 17.51 ± 0.56 °C and relative humidity of 67.69 ± 2.44%

throughout the 150-day storage period, which was defined to simulate real market conditions, in the interval between processing and sowing in commercial seed supply chains for the region, corresponding to the off-season for soybeans in the Brazilian Cerrado. Seed quality was monitored at 30-day intervals throughout the storage period.

The analyses were performed at the Post-Harvest Laboratory for Plant Products at IF Goiano – Rio Verde Campus. The evaluations were carried out for the 2022/2023 seed production season, in which seed storage was monitored before and after transport (upon receipt). Thus, this experiment was conducted in a completely randomized design, with seven treatments, one of which was a control treatment, corresponding to seeds before transport, and the other six were obtained by combining the types of tarpaulin and routes (WT×CAT, NT×CAT, WT×RON, NT×RON, WT×VR and NT×VR) in four replicates. That is, the seeds were evaluated in two periods (before and after transport), with two types of tarpaulin to cover the truck (white tarpaulin - thermal and normal tarpaulin - non-thermal) and for three logistics routes (Catalão, GO - which took about 10 hours to cover 653 km, Rondonópolis, MT - 7 hours to cover 377 km, and Vila Rica, MT - 18 hours to cover 1,148 km). Transportation times ranged from 7 to 18 hours, depending on the location. Before transport, the experiment was considered the control, and after transport, the other treatments.

The normal (non-thermal) tarpaulin, which is more common in transportation, is designed to cover the truck's load, preventing elements such as rain, dust and wind from damaging or compromising the goods being transported. The tarpaulin is usually attached using lashing systems such as ropes or elastic bands, which ensure that it is securely fastened during the journey. It was designed to cover the seeds in the truck's first trailer, made of high-tenacity polyester base fabric, coated with polyvinyl chloride on both sides and with an average thickness of 0.35 mm with a resistant structure, but does not fit the purpose of thermal insulation (Figure 1).

The white thermal tarpaulins used on the second trailer of the same truck had a multi-layer structure with thermal and mechanical functions, including an outer layer of high-density polyvinyl chloride with anti-UV treatment, an intermediate layer of expanded polyethylene for thermal insulation, and an inner reinforcement layer made of aluminized film with high solar radiation reflectivity, totaling a thickness of 1.20 mm (Figure 1). The white truck tarpaulin has a hooded or rectangular form for transporting perishable products in open-body trucks. For a long time, the thermal tarpaulin has been widely used for transporting pre-cooled fruit and vegetables: apples, grapes, carrots, greens and vegetables in general, both on short journeys and over long distances, with the aim of protecting the internal space from rising temperatures. And for this experiment it was used for the same purpose, but focused on the maintenance of relative humidity and temperature during the seed transportation.

Figure 1. Types of tarpaulin used in transportation: normal tarpaulin (orange, non-thermal) and white tarpaulin (thermal)

Approximately four big bags were used per logistics route evaluated. They were placed in two different wagons of the truck, each covered with a different type of tarpaulin - one thermal and one non-thermal. One of the sensors was inserted into the center of the seed mass, positioned approximately 90 cm deep inside the big bag. The other sensor was fixed to the outside of the seed mass, attached to the top handle of the big bag, located inside the truck body. The sensor used was the Elitech Gsp-6 digital temperature and humidity recorder (16,000 points, Cold Chain, model Gsp-6-10pack). The internal and external temperatures, as well as the relative humidity of the seed mass, were monitored at 30-minute intervals, from the time it left the Seed Processing Unit (SPU) until it reached the producers.

The lots sampled were subjected to assessments of moisture content, accelerated aging, germination, normal seedlings, abnormal seedlings, dead seeds, tetrazolium, emergence, electrical conductivity, dry mass and seedling length.

The moisture content of the seeds was determined by the gravimetric method, using an oven with forced air circulation at 105 ± 3 °C for 24 hours in four repetitions (BRASIL, 2009). The lots were sampled before and after transportation to assess the physiological quality of soybean seeds.

The seedling emergence test in sand was carried out in a greenhouse, using beds with a layer of washed sand that had been previously sieved to a particle size between 0.05 and 1.5 mm, then sterilized in an autoclave at 120 °C for 2 hours before use. The substrate was moistened by automatic daily sprinkling. Eight replicates of 25 seeds were used for each treatment, and the final count was made when emergence remained constant for three days (Maguire, 1962). The germination test was carried out according to the Rules for Seed Analysis (BRASIL, 2009), with four repetitions of 50 seeds each. Evaluation was made on the 5^{th} and 8^{th} day after sowing (DAS) - considering total germination in percentage (% TG), according to the criteria established in the Rules for Seed Analysis.

The length of the seedlings was assessed during the germination test, using four repetitions of 20 seeds each. On the 5^{th} day after the test, the length of the normal seedlings was assessed, calculating the mean length, and the results were expressed in mm per seedling.

The total dry mass (DM) was obtained from 20 seedlings collected from each repetition, which were placed separately in a forced ventilation oven at 80 °C and kept for 24 hours, with the results expressed in g per seedling, following the methodology proposed by Krzyzanowski (2020).

The accelerated aging test was performed on four repetitions of 50 seeds each. The repetitions were placed in a biochemical oxygen demand chamber, set at a temperature of 42 °C, and kept for 48 hours (Marcos Filho, 2015). After this period, the seeds were allowed to germinate, as described in the germination test. The results were expressed as a percentage of normal seedlings.

The electrical conductivity test was performed according to the methodology proposed by Vieira & Krzyzanowski (1999), using four repetitions of 50 seeds each. The previously weighed seeds were then soaked in 75 mL of deionized water and kept in a biochemical oxygen demand chamber regulated at 25 ºC for 24 hours. After this period, the electrical conductivity of the soaking solution was read and the results were expressed in $\mu S\ cm^{-1}\ g^{-1}$.

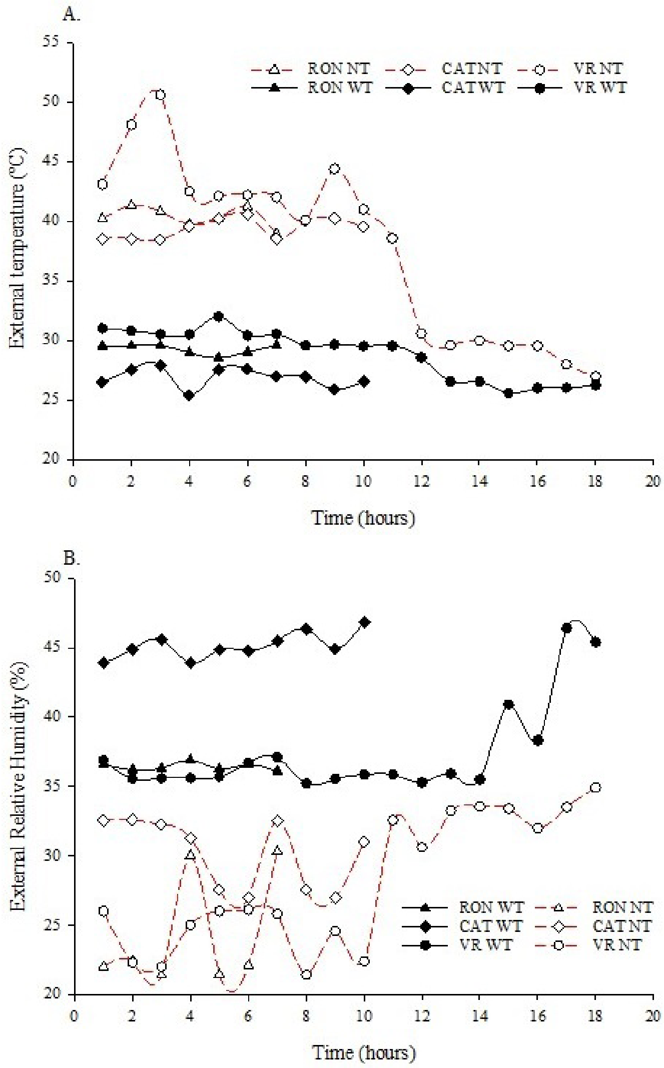
For the tetrazolium test, the analyses were carried out following the method of França Neto et al. (1998), in which 200 seeds per treatment were evaluated in four repetitions of 50 seeds, which were completely underwater in a tetrazolium solution (2-3-5, triphenyl tetrazolium chloride) at a concentration of 0.075%. Subsequently, the seeds were evaluated individually by sectioning them longitudinally through the embryonic axis between the cotyledons using a blade and classified according to the criteria of the methodology. The seeds were evaluated according to classes of vigor (1 to 3) and viability (1 to 5), following the methodology of França Neto et al. (1999). For analysis purposes, seeds in class 1 (intense and uniform red color throughout the embryo) were considered viable and of high vigor; those in class 2 (predominant red color, with some lighter or spotted areas) were classified as viable and of medium vigor; and those in class 3 (presence of red spots and whitish areas) were considered viable but not vigorous. In terms of viability, seeds in classes 1, 2 and 3 were considered viable, while classes 4 (partial death) and 5 (total death) were considered non-viable.

The data were analyzed using Sisvar 5.6® software and subjected to analysis of variance at $p \leq 0.05$, using the F test, followed by Dunnett test to compare each treatment with the control at $p \leq 0.05$. Before applying ANOVA, the assumptions of normality of residuals and homogeneity of variances were checked using the Shapiro-Wilk and Bartlett tests, respectively, both at $p \leq 0.05$. The degree of association between the variables was assessed using Pearson's correlation coefficients, also at $p \leq 0.05$, using the t-test (Ferreira, 2019).

Results and Discussion

Monitoring the external environment under the tarpaulin in the truck body showed fluctuations in air temperature and relative humidity from the place of departure to arrival at the final destination, with the mean temperature and relative humidity during the transportation time (7 hours for Rondonópolis/MT) of 29.25 ± 0.40 °C and 36.41 ± 0.27% for the white thermal tarpaulin, respectively; for the normal tarpaulin, the values were 40.36 ± 0.83 °C and 24.23 ± 4.05%. For Catalão/GO, transportation lasted 10 hours, with values of 26.88 ± 0.80 °C and 45.14 ± 0.95% for the white thermal tarpaulin and 39.43 ± 0.84 °C and 30.12 ± 2.52% for the normal tarpaulin. Finally, for Vila Rica/MT, where transportation lasted 18 hours, the values were 28.85 ± 2.107 °C and 37.40 ± 4.78% for the white thermal tarpaulin and 37.71 ± 7.539 °C and 28.07 ± 3.38% for the normal tarpaulin (Figure 2).

For analysis purposes, the experiment considered an ideal temperature range of 20.00 to 35.00 °C to be acceptable. In the truck with the normal tarpaulin, the temperature averaged 39.16 °C, while with the white thermal tarpaulin it was around 28.32 °C, showing a difference of around 10.86 °C from one tarpaulin to another, in addition to the high temperature peaks that were recorded with the normal tarpaulin. The white thermal tarpaulin, on the other hand, stood out in terms of temperature reduction and kept the relative humidity within the safest range, consistent with the characteristics and functionalities that this type of tarpaulin has in terms of insulation against temperature rises, with less change expected in terms of temperature rises inside the big bags.

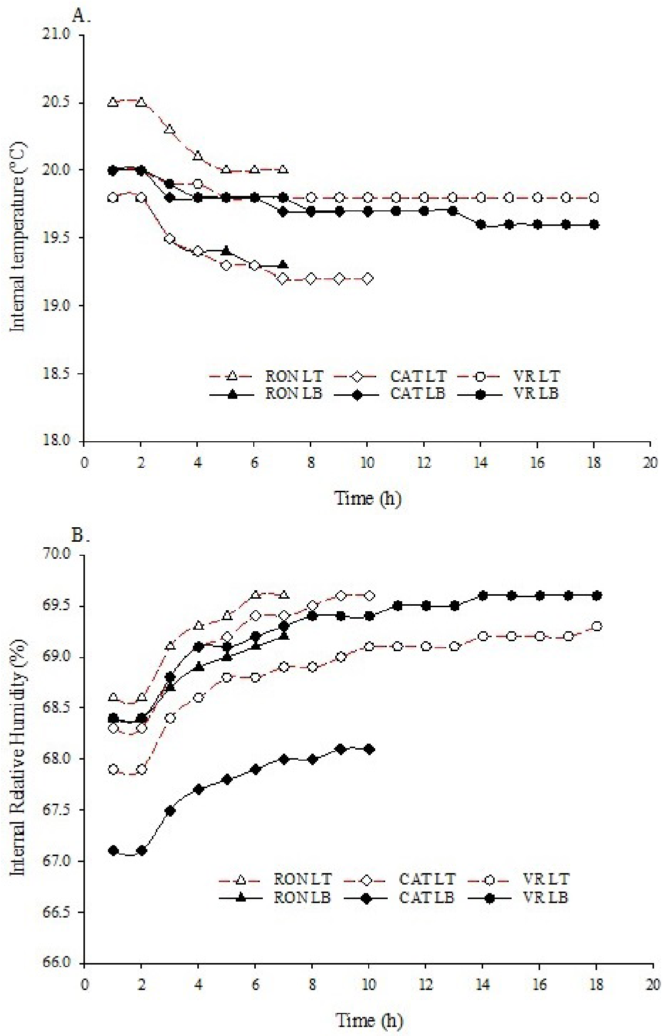


WT - White thermal tarpaulins; NT - Normal tarpaulins; CAT - Catalão/GO; RON - Rondonópolis/MT and VR - Vila Rica/MT

Figure 2. Variations in external temperature (A) and external relative humidity (B) of seed mass stored in big bags during transport to the final destination. The trucks were covered with two types of tarpaulins: white thermal tarpaulin (WT) and normal tarpaulin (NT), and transported on three different routes: Catalão/GO (CAT) for about 10 hours, Rondonópolis/MT (RON) for 7 hours and Vila Rica/MT (VR) for 18 hours

The internal temperature and relative humidity of the seed mass inside the big bags, from the SPU to arrival at the final destination, showed less variation throughout the period. From SPU to Rondonópolis/MT, the mean values for T and RH were 19.84 ± 0.22 °C and 67.98 ± 0.32% for the white thermal tarpaulin and 20.71 ± 0.23 °C and 67.68 ± 0.42% for the normal tarpaulin, respectively. For Catalão/GO, 20.12 ± 0.115 °C and 65.97 ± 0.38% were recorded on the white thermal tarpaulin and 20.57 ± 0.24 °C and 65.75 ± 0.49% on the normal tarpaulin. In Vila Rica/MT, 19.88 ± 0.13 °C and 68.56 ± 0.39% were recorded on the white thermal tarpaulin and 20.64 ± 0.07 °C and 66.70 ± 0.42% on the normal tarpaulin, for T and RH, respectively (Figure 3). In all situations, although the differences were not statistically significant, the seeds covered by white (thermal) tarpaulin consistently showed slightly lower values compared to those covered by normal (non-thermal) tarpaulin.

When it comes to transportation, a critical factor in seed preservation is the temperature inside the truck body,



WT - White thermal tarpaulins, NT - Normal tarpaulins, CAT - Catalão/GO, RON - Rondonópolis/MT and VR - Vila Rica/MT

Figure 3. Variations in internal temperature (A) and internal relative humidity (B) of seed mass stored in big bags during transport to the final destination. The trucks were covered with two types of tarpaulins: white thermal tarpaulin (WT) and normal tarpaulin (NT), and transported on three different routes: Catalão/GO (CAT) for about 10 hours, Rondonópolis/MT (RON) for 7 hours and Vila Rica/MT (VR) for 18 hours

suggesting that the dark-colored tarpaulins (non-thermal), which are generally the most used to cover the truck, be replaced with white thermal tarpaulins. On the other hand, the inside of the seed mass was not influenced by the external environment, probably due to the shorter exposure time, adequate packaging and the fact that the repetitions were stored under a controlled condition. Due to their internal structure, surface, and physical properties, such as low thermal conductivity, seeds offer the best conditions to be cooled and thus remain for a long time (Kibar, 2015; Leal et al., 2023). However, also noteworthy is the use of packaging that mitigates the impact of the external environment (Capilheira et al., 2020).

This highlights the importance of both seed quality and packaging material in managing seed health, particularly under ambient storage conditions (Odokonyero et al., 2021; Ogwu et al., 2024). Packaging has several functions in the seed market, such as separation and identification of seeds, ease of transport and storage, and protection of seeds against attack by organisms and environmental variations (Coradi et al., 2020b). Therefore, packaging must have good resistance to transport, porosity or impermeability, flexibility or rigidity, durability, ease of printing, transparency or opacity, and resistance to insects and rodents (Bakhtavar et al., 2019).

In general, the temperature variations are attributed to the transportation of seeds in unsafe trucks, since the cargo compartments do not have adequate ventilation. In this situation, the maximum protection provided is the covering with waterproof tarpaulins, leaving the seeds exposed to unfavorable conditions during transport, which usually occur from September to October, months with rainfall.

Most rural properties or resale companies do not have adequate facilities for storing seeds, so it is recommended that the seeds are kept on the property for a short time. In other words, the ideal situation is for the seeds to arrive as close to sowing time as possible.

Table 1 shows the degree of association between the variables analyzed using Pearson's correlation coefficient. There was a higher correlation between moisture content and normal seedlings ($r = + 0.76$, $p < 0.01$), which indicates that, for most of the variables, a higher percentage of moisture content indicated a higher percentage of normal seedlings. A higher correlation was also observed between the percentage of abnormal seedlings and ungerminated seeds ($r = + 0.73$, $p < 0.01$), indicating that a higher percentage of abnormal seedlings point to a higher percentage of dead seeds.

When correlating the percentage of normal seedlings (Table 1) with the percentage of abnormal seedlings, a high negative correlation was observed ($r = - 0.87$, $p \leq 0.01$); the lower the number of abnormal seedlings, the higher the percentage of normal seedlings.

The quality of the seeds that reach the farmer is crucial to successful production. A good germination rate and high vigor are the first factors that will allow healthy plants to emerge and crops to establish quickly, which will result in good yield. However, there are two moments that can affect the initial quality of seeds if the right conditions are not in place and monitored: transportation and storage.

Table 1. Pearson's correlation analysis between soybean seed quality variables

	GER	NS	AS	US	SL	48 h	EME	VG	VIAB	DM	EC
MC	0.49**	0.76**	-0.73**	-0.48**	0.10^{ns}	0.31^{ns}	0.27^{ns}	0.30^{ns}	0.43*	-0.06^{ns}	- 0.54**
GER		0.64**	-0.73**	-0.99^{ns}	0.35^{ns}	0.28^{ns}	-0.08^{ns}	0.17^{ns}	0.31^{ns}	0.08^{ns}	-0.13^{ns}
NS			-0.87**	-0.62**	0.45*	0.47*	0.27^{ns}	0.19^{ns}	0.32^{ns}	-0.12^{ns}	-0.38*
AS				0.73**	-0.26^{ns}	-0.34^{ns}	-0.06^{ns}	-0.22^{ns}	-0.26^{ns}	0.29^{ns}	0.32^{ns}
US					-0.31^{ns}	-0.24^{ns}	0.13^{ns}	-0.12^{ns}	-0.26^{ns}	-0.02^{ns}	0.09^{ns}
SL						0.54**	0.35^{ns}	0.08^{ns}	0.32^{ns}	0.49**	-0.24^{ns}
48 hours							0.25^{ns}	0.15^{ns}	0.34^{ns}	0.24^{ns}	-0.20^{ns}
EME								0.17^{ns}	0.42*	0.44*	-0.63**
VG									0.36^{ns}	0.33^{ns}	-0.25^{ns}
VIAB										0.59**	-0.62**
DM											-0.28^{ns}

MC - Moisture content (% w.b.), GER - Germination (%), NS - Normal seedlings (%), AS - Abnormal seedlings (%), US - Ungerminated seeds (%), 48 hours - Accelerated aging for 48 hours (% NS); EME - Emergence (%); Tetrazolium VG - Vigor (%); Tetrazolium VIAB - Viability (%); DM - Dry mass of seedlings (g per seedling); SL - Seedling length (mm) and EC - Electrical conductivity (μS cm^{-1} g^{-1})

Table 2, referring to the analysis of variance (ANOVA), revealed a significant effect of the treatments ($p \leq 0.01$ or $p \leq 0.05$) on most of the physiological variables evaluated, including moisture content (MC), emergence (EMER), electrical conductivity (EC), seedling length (SL), seedling dry mass (DM), viability (VIAB), germination (GER), normal seedlings (NS), abnormal seedlings (AS) and ungerminated seeds (US).

The exceptions were vigor (VG), which showed no significant difference between the treatments, and accelerated aging for 48 hours, which was only significant at the 5% level ($p \leq 0.05$). These results indicate that the treatments applied directly influenced the physiological quality of the seeds, especially electrical conductivity, germination and viability, parameters which are sensitive to the variations imposed by transportation and storage conditions.

According to the mean values of moisture content (Figure 4A), only the RON WT, VR WT and VR NT treatments had lower values than the control, 7.43, 7.31 and 7.17% w.b., respectively, while the other treatments were similar. According to Ducatti et al. (2019), standardizing the moisture content of seeds is essential for standardizing evaluations, with a view to obtaining consistent results.

It should be noted that high moisture content levels do not guarantee high physiological quality and, under high temperatures, can accelerate seed deterioration. This highlights the importance of controlling moisture content before transport and the strategic use of thermal tarps to minimize temperature variations and preserve seed quality. Seed moisture content plays a critical role in determining the rate and extent of physiological activities in seeds (Tangney et al., 2019).

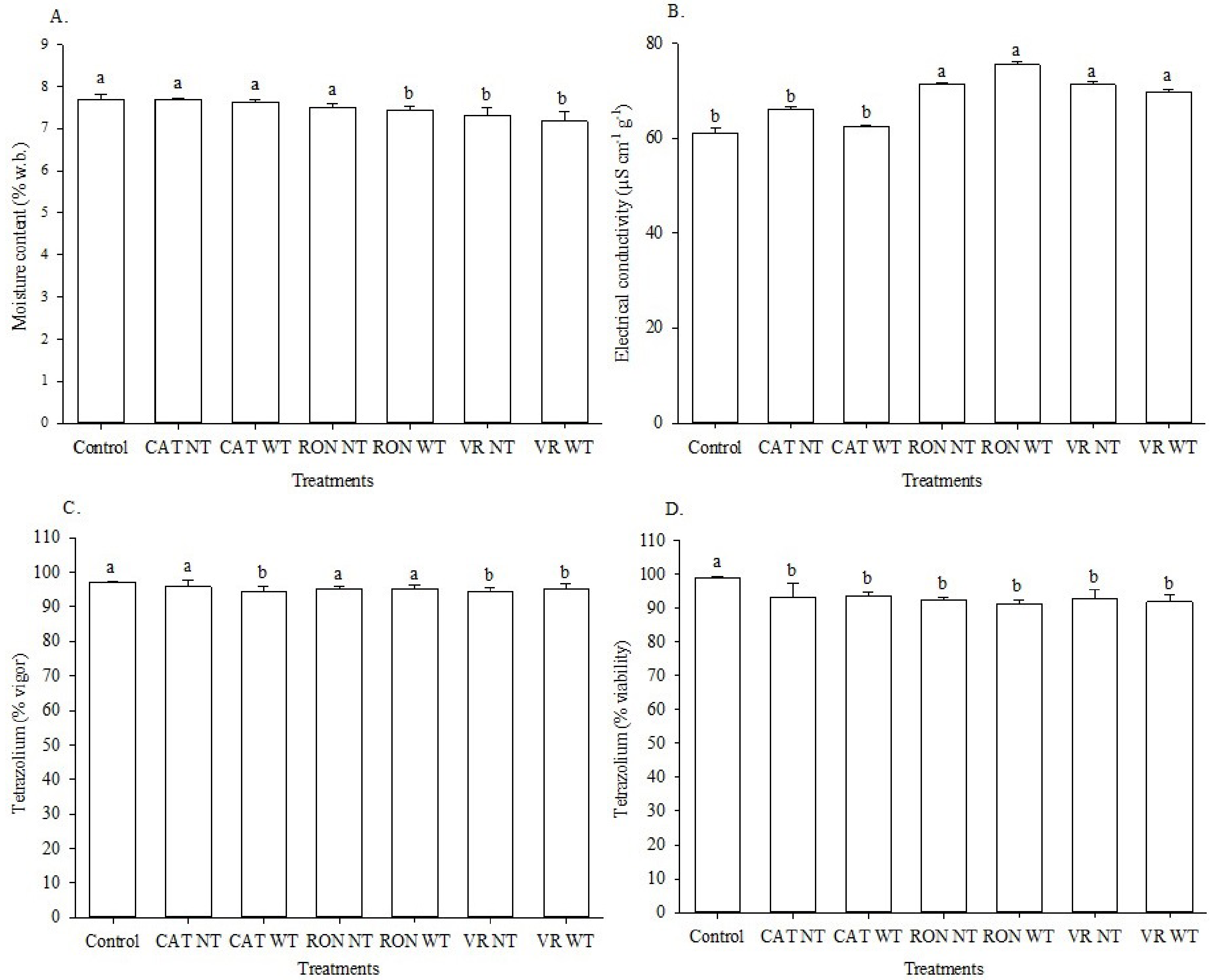
For electrical conductivity, the values obtained in the RON NT, RON WT, VR NT and VR WT treatments were higher than those obtained in the control (Figure 4B), ranging from 69.78 to 75.44 μS cm^{-1} g^{-1}. The electrical conductivity of the seeds showed high values, and according to Marcos Filho (2015), this test is related to the capacity for membrane reorganization during soaking, indicating that the greater the amount of exuded ions, the greater the deterioration of the seeds. However, as this process progresses, the amount of leachates released by vigorous seeds stabilizes, mainly due to the reorganization of membranes, favoring the classification of lots into quality levels (Dhaliwal & Angeles-shim, 2022).

With regard to vigor values, the CAT NT, RON NT and RON WT treatments were similar to the control, showing higher values, indicating the shorter time they were exposed to transportation. These treatments also showed superior vigor when compared to those exposed for a longer time to transportation, while the others differed from the control (Figure 4C). The vigor found, even after the introduction of the treatments, ranged from 94.50 to 97.00%, indicating that a good quality seed has a high percentage of germination and vigor, physical purity, adequate genetics and health. In the development of the crop, other factors interfere with yield; however, if the seed is of high vigor, it will have greater potential to overcome adverse environmental conditions (Pereira et al., 2021). Due to the importance of the seed in the establishment of the crop, as it carries the genetic material that allows the crop to reach its yield potential, and taking into account the new

Table 2. Mean squares obtained by analysis of variance for the physiological variables of soybean seeds subjected to different transportation conditions

SV	DF	Mean squares				
		MC	EMER	EC	SL	DM
Treat	6	0.15**	39.27**	106.99**	524.16**	0.04**
Error	21	0.01	7.83	0.31	34.14	0.00
CV (%)		1.77	3.01	0.81	4.63	4.02
		VG	VIAB	48 h	GER	NS
Treat	6	2.98^{ns}	24.89**	10.83*	39.14**	331.33**
Error	21	1.56	4.17	2.82	1.77	16.27
CV (%)		1.31	2.18	1.75	1.37	5.03
		AS	US			
Treat	6	11,195.74**	37.24**			
Error	21	6.52	1.80			
CV (%)		9.07	48.44			

**Significant at 1% by the F test; *Significant at 5% by the F test; NS - Not significant, CV - Coefficient of variation



Pairs of equal letters between each treatment and the control do not differ by Dunnett's test at p ≤ 0.05 (n = 4); WT - White tarpaulins, NT - Normal tarpaulins, CAT - Catalão/GO, RON - Rondonópolis/MT and VR - Vila Rica/MT

Figure 4. Mean values of moisture content (A), electrical conductivity (B), tetrazolium - vigor (C) and tetrazolium - viability (D) of soybean seeds before and after transport under different conditions and logistical routes

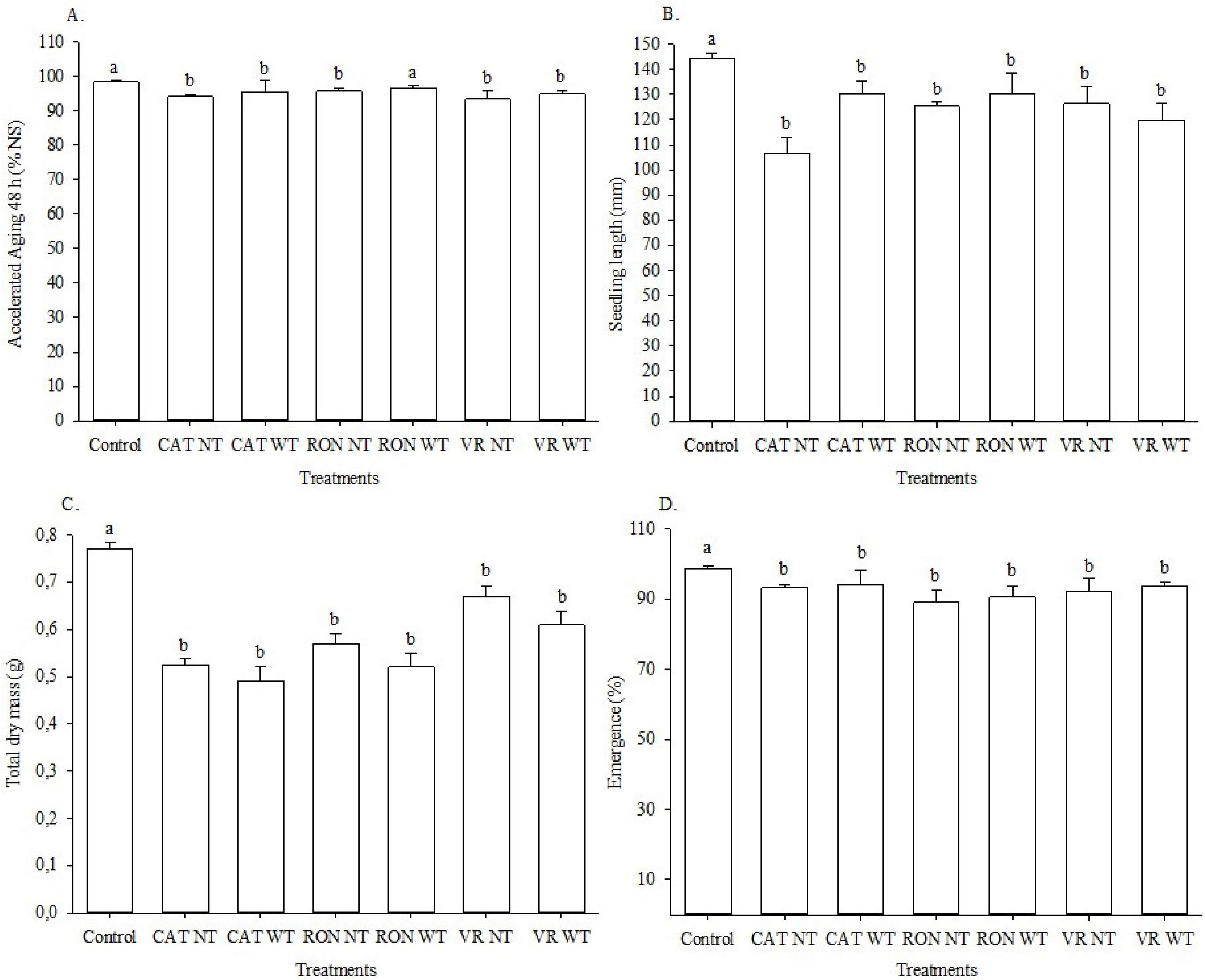
technologies, quality insurance is essential to achieve adequate yields (Maculan et al., 2021).

The viability values showed random behavior in relation to the different treatments (routes × tarpaulins), although a downward trend was visible compared to the control (before transport), reducing from 98.83 to 91.37%, since for all conditions the absolute values obtained in each treatment were always lower than the control (Figure 4D). Vigor and viability, which are linked to the germination potential of seeds, are essential characteristics for good production as this is the result of good sowing, through the use of quality seeds, that is, seeds with high vigor and viability, which are influenced by the field conditions to which the plants were subjected in addition to the storage conditions they receive after being harvested (Rodrigues et al., 2020).

The tetrazolium test is extremely important when it comes to assessing the physiological quality of seeds, as it evaluates seed viability and vigor, as mentioned by Mangena (2021), the concept of seed viability is related to seed vigor, which refers to the quality attributes of seeds that are distinguished by successful germination and establishment of seedlings in cultivated fields.

As for the accelerated aging values at 48 hours, the behavior between treatments (routes × tarps) was different, although the downward trend was visible compared to the control (before transport), going from 98.83 to 93.50% of normal seedlings generated, except for RON WT, which showed the same behavior as the control with a value close to 96.75% NS (Figure 5A). The reductions were minimal when referring to the exposure of seeds to a stress test, that is, the percentage of normal seedlings in accelerated aging was not reduced below 93.50%, which is a positive result, since the aging test is important to verify which seeds are more vigorous and, therefore, more tolerant to high temperatures and relative humidity (Araújo et al., 2021). Despite this, Demir et al. (2019) indicate that this test is quite efficient for evaluating seed performance in relation to germination capacity.

With regard to seedling length and dry mass, the values obtained in each treatment were always lower than those found in the control (Figures 5B and C), with averages varying



Pairs of equal letters between each treatment and the control do not differ by Dunnett's test at $p \leq 0.05$ (n= 4); WT - White tarpaulins; NT - Normal tarpaulins; CAT - Catalão/GO; RON - Rondonópolis/MT; and VR - Vila Rica/MT

Figure 5. Mean values of the accelerated aging test for 48 hours (A), seedling length (B), total dry mass (C) and seedling emergence (D) of soybean seeds before and after transport under different conditions and logistical routes

from 106.57 to 130.10 mm for seedling length and 0.492 to 0.670 g for total dry mass, bearing in mind that the control stood at 144.35 mm and 0.770 g. The data on seedling length explains the integrity of the embryo and the use of reserve tissues (Teixeira et al., 2020). It is also important to note that the quality of soybean seeds is intrinsically linked to their physiological quality, thus affecting their ability to produce vigorous seedlings (Wijewardana et al., 2019). Similarly, according to Prado et al. (2021) the ability of a seedling to produce well and the length of its root are important factors in obtaining a plant stand with uniformity in crop production.

As for the emergence values, the downward trend was visible compared to the control (before transportation) (Figure 5D). It should be noted that the physical integrity of soybean seeds is crucial for their effective performance in the field, considered a key factor in soybean production, establishing rapid emergence and promoting proper seedling establishment. In addition, seed germination and emergence are critical stages of plant development that significantly influence subsequent stages of plant development in the field, indicating the economic and ecological importance of seeds (Dueñas et al., 2024).

It was possible to observe that the emergence values varied from 89.00 to 98.83%, corroborating that high-vigor seeds show rapid and uniform germination and emergence performance, especially under stressful environmental conditions (Chen et al., 2022; Tao et al., 2023).

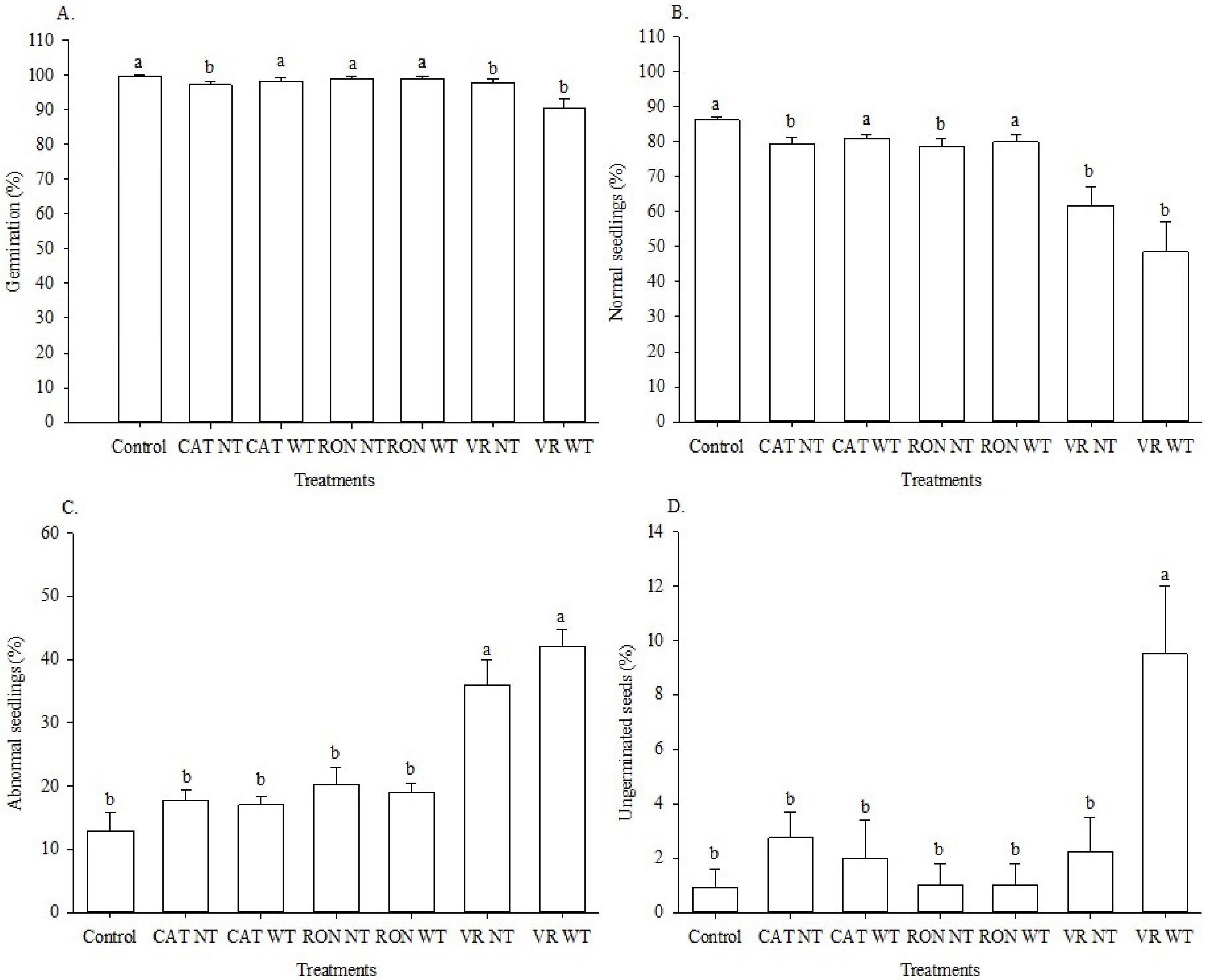
In terms of germination, the CAT NT, VR NT and VR WT treatments showed a reduction in values and a different behavior from the control (Figure 6A), with a variation from 99.75 to 97.25, 97.75 and 90.50%, respectively, with the introduction of the treatments after transportation. On the other hand, the values obtained for the germination percentage of the seeds showed that the seeds subjected to these treatments were of high physiological quality, since the germination capacity of the lot of seeds under laboratory conditions must be greater than 80%, which is the minimum standard for marketing seeds in some countries such as Brazil (BRASIL, 2013).

Matera et al. (2019) highlighted the association of the germination test with the accelerated aging test and also with field emergence tests, thus showing that good results in the accelerated aging test indicate storage potential and also the potential for good seedling stand formation, which is essential for high grain yields. In addition, for the germination of seeds to be viable, it is essential to take into account their physiological qualities, moisture content, vigor, and viability (Barroso et al., 2022).

As for the percentage of normal seedlings, only the CAT WT and RON WT treatments behaved similarly to the control, while the others were lower than the control (Figure 6B), with values of 80.00 to 81.00%, respectively. The values of the other treatments ranged from 79.50 to 48.50%. The white color of the tarp significantly reduces heat absorption, but the quality of the tarp is necessary to prevent the material from breaking and to help preserve the quality of the exposed seeds. It can be observed that, with regard to abnormal seedling values, only VR NT (35.89%) and VR WT (48.00%) performed differently from the control (Figure 6C), showing a higher percentage of abnormal seedlings coinciding with the greater distance traveled.

For the percentage of ungerminated seeds (Figure 6D), the behavior was divergent, as most of the treatments were similar to the control, ranging from 0.910 to 2.750%, except for VR WT (9.50%), which showed a higher value than the others, due to the greater distance traveled and longer time of exposure to the adverse conditions.

In general, the external variation of approximately 11 °C did not affect the internal temperature of the seed mass, due to the low thermal conductivity and insulation of the packaging. Internal monitoring was performed by sensors in the center of the big bag, adequately representing the average condition of the 1,000 kg transported, despite possible local variations. Factors such as transport time and route characteristics influenced the results, as the route to Vila Rica/MT had unpaved roads and was more exposed to dust and vibrations. For Catalão/GO, the truck covered a longer distance on paved highways and at high altitudes, with moderate variations in temperature and humidity. Meanwhile, for Rondonópolis/MT, there was a combination of paved and unpaved sections in a hot and dry climate. However, according to Ciscon et al. (2021), all



Pairs of equal letters between each treatment and the control do not differ by Dunnett's test at $p \leq 0.05$ (n=4); WT - White tarpaulins; NT - Normal tarpaulins; CAT - Catalão/GO; RON - Rondonópolis/MT; and VR - Vila Rica/MT

Figure 6. Average values for germination (A), normal seedlings (B), abnormal seedlings (C), ungerminated seeds (D) of soybean seeds transported under different conditions and logistics routes

this genetic and physiological potential can be compromised by the natural process of deterioration and aging.

This resulted in a slight reduction in seed quality after transport, but even with this reduction, the seeds remained within commercial standards, showing greater potential when subjected to adverse conditions, as they were lots with greater vigor. Seed vigor is the expression of a set of physiological processes determined by cellular signaling mechanisms, involving the allocation, hydrolysis, and translocation of assimilates to the embryo (Pereira, 2020), which are reflected in seed performance after sowing, such as rapid and uniform emergence, with normal seedling development within a wide range of environmental conditions (Costa et al., 2021).

Among all the factors that drive significant increases in production and increase the productive capacity of Brazilian soybeans is the use of quality seeds (Filassi et al., 2021).

Conclusions

1. Digital sensors successfully tracked temperature and humidity variations during soybean seed transport, enabling real-time quality assessment.
2. Transport distance showed inverse relationship with seed quality variables, with routes >1,000 km showing statistically significant but commercially acceptable reductions in vigor (2.25% decrease) and viability (6.46% decrease).
3. Thermal tarpaulins reduced external temperature variation by approximately 11 °C compared to conventional covers, though internal seed mass temperature remained stable (19-20 °C) regardless of cover type.
4. All seed lots maintained quality parameters above commercial standards (>90% germination), suggesting current logistics practices are adequate for short-term transport under study conditions.

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