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Innovative techniques for storing wheat seeds at ambient temperature and under refrigeration

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Técnicas inovadoras no armazenamento de sementes de trigo em temperatura ambiente e sob refrigeração

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ABSTRACT: In Southern Brazil, ambient temperatures are high between wheat harvest and sowing of the new crop, posing a challenge for seed conservation. Therefore, to maintain physiological quality and productive potential, seeds need to be properly stored. This study evaluated the impact of different atmospheric conditions and the application of nitric oxide (NO) on the conservation of wheat seeds stored at different temperatures. Wheat seeds 'ORS Feroz' were stored under the following conditions: control, modified atmosphere (MA), two NO concentrations (50 and 500 µL L^{-1}), controlled atmosphere (CA) with high CO_2 (50 kPa) and combined with low O_2 (1 kPa O_2 + 50 kPa CO_2), all under two temperatures: exposed to the environment and refrigerated (10 ºC). After five months, germination, vigor, electrical conductivity, and emergence in seedbeds were evaluated. Refrigeration preserved better seed viability, with less vigor loss and lower electrical conductivity compared to exposure to ambient temperature. At ambient temperature, CA (both with high CO_2 or combined with low O_2) and NO (500 µL L^{-1}) were highlighted in maintaining quality. However, MA also preserved seed quality, even at ambient temperature, and is a lower cost strategy. It can be concluded that storage techniques such as atmosphere control (MA and CA) and NO treatment (500 µL L^{-1}) can be important strategies to prolong wheat seed viability, especially when refrigeration system is not adopted.
Key words: *Triticum aestivum* L., controlled atmosphere, nitric oxide.

Técnicas inovadoras no armazenamento de sementes de trigo em temperatura ambiente e sob refrigeração

RESUMO: No Sul do Brasil, a temperatura ambiente apresenta-se elevada entre a colheita do trigo e o plantio da nova safra, representando um desafio para a conservação da semente. Deste modo, para garantir a manutenção da qualidade fisiológica e do potencial produtivo, as sementes necessitam ser armazenadas de forma adequada. Neste sentido, esta pesquisa objetivou avaliar o impacto de diferentes condições atmosféricas e da aplicação de óxido nítrico (NO) na conservação das sementes de trigo armazenadas em diferentes temperaturas. Para alcançar o objetivo, sementes de trigo da cultivar ORS Feroz foram armazenadas nas seguintes condições: a) controle; b) atmosfera modificada (AM); c) aplicação de duas doses de NO (50 e 500 µL L^{-1}); d) atmosfera controlada (AC) com alto CO_2 (50 kPa); e e) associado ao baixo O_2 (1 kPa O_2 + 50 kPa CO_2). Além disso, as sementes foram expostas sob duas temperaturas (ao ambiente e refrigerada (10 ºC)), independentemente das condições armazenadas. Após cinco meses, avaliou-se germinação, vigor, condutividade elétrica e emergência em canteiros. Os resultados mostram que a refrigeração preservou melhor a viabilidade das sementes, com menor perda de vigor e menor condutividade elétrica, em comparação com a temperatura ambiente. Sob temperatura ambiente, o uso de AC (tanto com alto CO_2 como combinado com baixo O_2) e o NO (500 µL L^{-1}) destacaram-se na manutenção da qualidade. Porém a AM preservou a qualidade das sementes, mesmo em temperatura ambiente, sendo uma estratégia de menor custo. Portanto, conclui-se que técnicas de armazenamento como controle da atmosfera (AM e AC) e aplicação de NO (500 µL L^{-1}) podem ser estratégias importantes para prolongar a viabilidade das sementes de trigo, especialmente na ausência de sistema de refrigeração.
Palavras-chave: *Triticum aestivum* L., atmosfera controlada, óxido nítrico.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the main winter crops in Brazil, especially in Paraná (PR) and Rio Grande do Sul (RS) States. Between 2009 and 2019, an average of 2.2 million hectares were cultivated, with an annual production of 5.4 million tons. However, in the 2024/25 season, production decreased markedly, primarily due to reduction in the planted area (14.2%) and adverse weather conditions in Paraná (CONAB, 2025). The introduction of wheat by colonizers found favorable soil and climate conditions in RS (BRUM & HECK, 2005).

However, wheat farming faces challenges such as frost, fungal diseases (head blight and wheat blast), competition with the wheat produced in Argentina, with higher industrial quality (CASTRO et al., 2018), as well as logistical limitations and high costs. In 2018, RS accounted for a third of national production, with a mean yield of 2,467 kg ha^{-1},

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reaching up to 3,560 kg ha^{-1} in the state's northeast (CASTRO et al., 2018). However, climate variations negatively affect grain yield and quality, reducing the number and grains mean weight (RIBEIRO et al., 2012a). Unlike summer crops, for wheat, between harvesting and sowing the new cultivation (May and June in South Brazil), the seeds are exposed to higher air temperatures, above 20 °C, which accelerates deterioration (DEVILLA et al., 2004).

Seed quality is directly linked to storage conditions (MARCOS FILHO, 2005). Hot and humid environments favor fungal infestation and decrease seed vigor and germination (SCARIOT et al., 2018). High-quality seeds should have a germination rate above 85% and sufficient vigor to emerge even under adverse conditions (KUMAR et al., 2024). However, wheat seeds are commonly stored under ambient conditions, which may lead to increases in moisture content and temperature, promoting fungal proliferation and embryo deterioration (WANG et al., 2020). Furthermore, crop producers sometimes store seeds at moisture contents above the ideal range (8–12%) due to the limited capacity of aeration systems or as a strategy to reduce drying costs, potentially compromising seed quality and storage duration (NITHYA et al., 2011). In wheat seeds stored at 14% moisture content, refrigerated storage (15°C) maintained a high germination rate, suppressed aflatoxin incidence, and contributed to the preservation of processing quality (LI et al., 2026). Refrigerated storage promotes the activity of antioxidant enzymes and maintains cellular integrity (BERGHETTI et al., 2026), thereby suppressing catabolic reactions during seed storage, even at high moisture content (NITHYA et al., 2011).

The adoption of sophisticated techniques such as controlled atmosphere (CA) and modified atmosphere (MA) may be promising in preserving seed quality. CA actively regulates O_2 and CO_2 partial pressures (with reduction in pO_2 and increase in pCO_2, balanced with N_2), while MA uses selective barriers in packaging (BRACKMANN et al., 2005). RIBEIRO et al. (2012b) reported lower electrical conductivity in palm heart seeds under MA. In soybean seeds positive results were observed with CA storage, resulting in higher physiological quality of the seeds (BERGHETTI et al., 2026). These techniques, combined with low temperatures, extend the soybean seed longevity (LUDWIG et al., 2021).

Nitric oxide (NO) has been studied as a preservative agent for its role in germination (JACOBSEN et al., 2013) and in reducing oxidative stress (PIRES et al., 2016). NO acts in the dormancy regulation and activates antioxidant enzymes such as superoxide dismutase (SOD) and catalase (CAT) (REN et al., 2020; CIACKA et al., 2022). In sesame seeds, sodium nitroprusside (SNP), a compound that generates NO, increased antioxidant enzymes activity and eliminated reactive oxygen species (ROS) (PIRES et al., 2016). NO also inhibits abscisic acid (ABA), promoting seed germination (SARATH et al., 2006) and radicle and coleoptile growth (JACOBSEN et al., 2013), even under stress (SHI et al., 2025).

Although, storage conditions are among the main factors influencing seed quality and successful crop establishment (BERGHETTI et al., 2026), there are still few studies evaluating the effects of postharvest products, gas concentrations, and storage temperatures on wheat seed quality. Therefore, this study evaluated different storage conditions for preserving the viability, vigor, and germination potential of wheat seeds stored for five months under ambient or refrigerated temperature.

MATERIALS AND METHODS

The experiment was conducted at the Post-Harvest Research Center (NPP), Plant Science Department, of the Universidade Federal de Santa Maria (UFSM), in Santa Maria, RS. 'ORS Feroz' wheat seeds were harvested in October 2023. Initial water content (14.5%) was determined by the oven-drying method (105 ± 3 ºC for 24 h), at the Seed Analysis Laboratory (LAS -UFSM), according to the RAS - *Regras para Análise de Sementes* (BRASIL, 2009).

The seeds were homogenized, divided into 500 g samples (three replicates per treatment) and packaged in kraft paper bags. Six different storage conditions were evaluated (Table 1) (control, MA, CA, and application of nitric oxide (NO) at 50 or 500 µL L^{-1}), at 10 ºC, and ambient conditions without temperature control (Figure 1). The CA conditions were employed in hermetically sealed mini-silos (24 L), via nitrogen (N_2) injection, obtained from a Pressure Swing Adsorption (PSA) generator, to reduce pO_2 and by injecting carbon dioxide (CO_2) from high-pressure cylinders. O_2 and CO_2 partial pressures were monitored weekly using a Siemens Ultramat-23 analyzer and adjusted to maintain the predefined set points (Figure 2).

For MA, seeds were sealed in 0.15 mm nylon-polyethylene bags (30 × 30 cm) with a heat sealer. NO was applied inside hermetic mini-silos (24 L) obtained from a high-pressure cylinder (1,000 µL L^{-1}). As NO can be inactivated through its reaction with O_2, forming NO_2 and NO_3^-, its application is

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Table 1 - Storage conditions and temperatures adopted for wheat seeds stored over a five-month period. MA: modified atmosphere; NO: nitric oxide; CA1: controlled atmosphere only with higher CO_2; CA2: controlled atmosphere with low O_2 associated to high CO_2.

Storage Conditions	Temperature
Control	10 °C
MA (hermetically sealed in a plastic bag)	10 °C
NO (50 µL L^{-1}) applied at 1 kPa de O_2	10 °C
NO (500 µL L^{-1}) applied at ambient air (21 kPa O_2)	10 °C
CA_1 (50 kPa CO_2)	10 °C
CA_2 (1 kPa O_2 + 50 kPa CO_2)	10 °C
Control	Ambient
MA (hermetically sealed in a plastic bag)	Ambient
NO (50 µL L^{-1}) applied at 1 kPa de O_2	Ambient
NO (500 µL L^{-1}) applied at ambient air (21 kPa O_2)	Ambient
CA_1 (50 kPa CO_2)	Ambient
CA_2 (1 kPa O_2 + 50 kPa CO_2)	Ambient

recommended under low-O_2 conditions or, alternatively, at higher concentrations to compensate for oxidative NO losses. Therefore, to obtain a concentration of 50 µL L^{-1}, the mini-silo was previous flushed with N_2 until the pO_2 reached 1 kPa, thereby minimizing the NO oxidation. For the 500 µL L^{-1} treatment, ambient O_2 conditions were maintained. After NO application, the mini-silos remained hermetically sealed for 24 h, allowing NO diffusion into the mini-silo headspace and its absorption by the seeds.

After five months storage, the seeds physiological quality was evaluated by the following tests: (i) electrical conductivity, with three replicates of 50 seeds immersed in 75 mL distilled water for 24 h at 20 ºC; (ii) germination, with three replicates of 100 seeds placed on moistened germitest paper, kept at 20 ºC, and counted on the 9th day; (iii) vigor (first count), performed on the 5th day; and (iv) emergence in the seedbed, evaluated 15 days after sowing, considering wheat seedlings with visible cotyledonary loops as emerged. All tests were conducted according to the RAS (BRASIL, 2009).

To characterize the external environment, maximum and minimum air temperature data were collected from the automatic weather station, at National Institute of Meteorology's, 200m away from the experiment location. The data (maximum and minimum air temperature) to characterize the seed storage site (internal) were obtained from an ITLOG-90 datalogger installed near to the mini-silos. Hourly determinations were recorded, and graph was

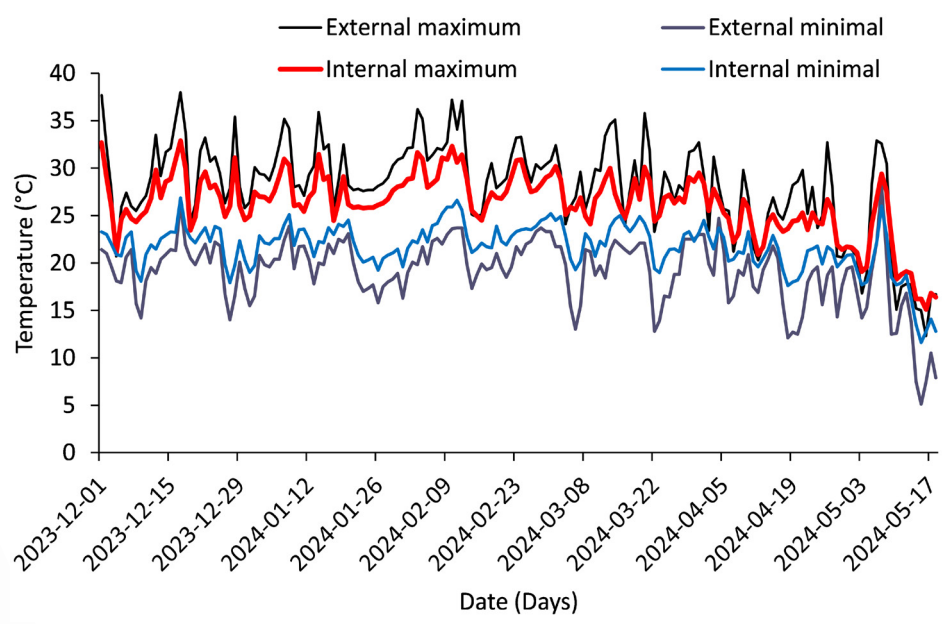


Figure 1 - Daily maximum and minimum air temperatures of the ambient condition where the wheat seeds were stored (internal) and at the meteorological station (external) from December until the end of storage without refrigeration.

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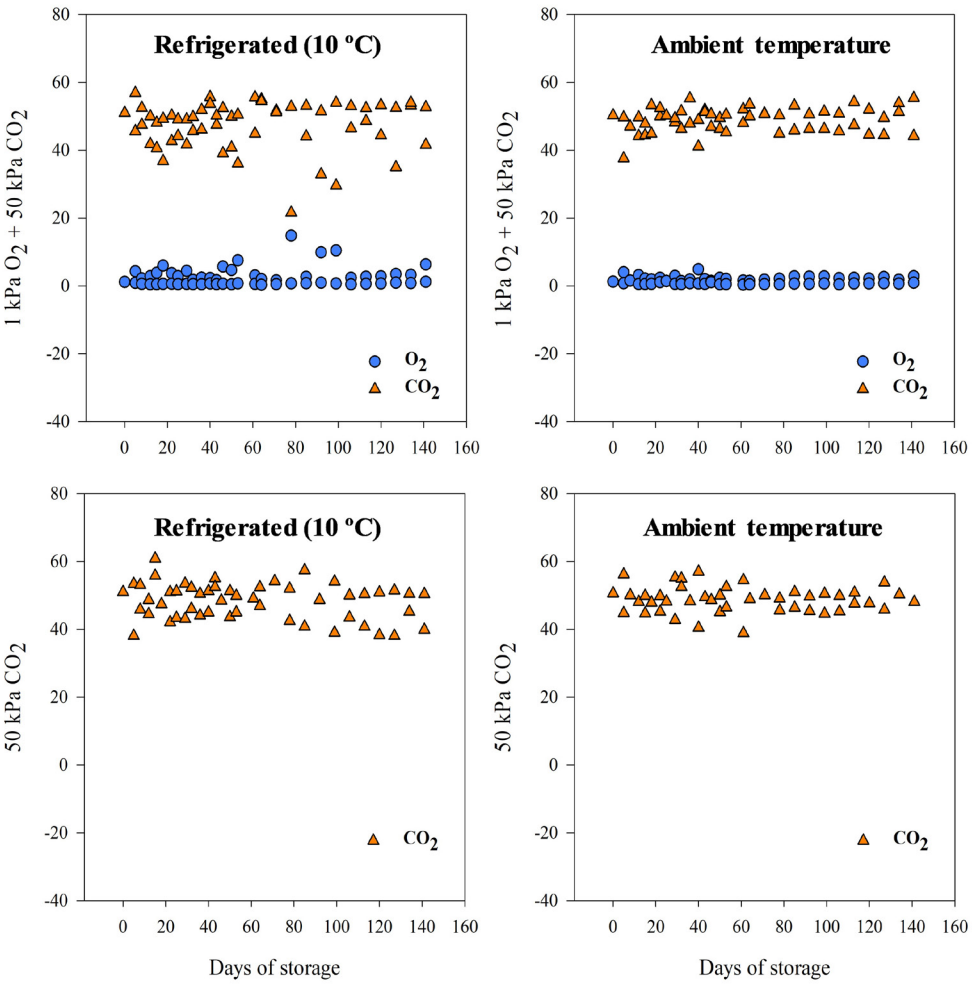


Figure 2 - Variation of O_2 and CO_2 partial pressure during the five months of storage under two controlled atmosphere conditions (50 kPa CO_2 and 1 kPa O_2 + 50 kPa CO_2), at refrigerated (10 ºC) and ambient temperatures. Determinations were taken once a week.

made recording the daily maximum and minimum values (Figure 1).

A completely randomized design was used, in a 2 × 6 factorial scheme (temperature × storage condition), with three replicates. Data was subjected to analysis of variance (ANOVA), with means compared by Scott-Knott test ($P < 0.05$), using SISVAR v.5.6 software (FERREIRA, 2019).

RESULTS AND DISCUSSION

The external environment (obtained from the automatic weather station - National Institute of Meteorology A803) had a much higher and more variable air temperature than the internal environment (data collected from datalogger - Figure 1). Even so, the average maximum temperature sometimes exceeded 30 ºC. Temperature fluctuations in the uncooled environment were due to external weather conditions. The maximum and minimum air temperatures in the internal environment were within the maximum and minimum limits of the external environment on 83% and 98% of days, respectively.

Germination test

The germination of 'ORS Feroz' wheat seeds was influenced by the interaction between temperature and storage conditions. At 10 ºC, there was no difference between treatments. At ambient temperature, both CA conditions, and MA maintained

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higher germination (Figure 3). The application of NO demonstrated no positive effect on seed germination, irrespective of the temperature. In the comparison between temperatures, only the control resulted in higher germination under refrigerated conditions. This reinforces the negative effect of high temperatures, which accelerates damage such as loss of membrane integrity and lipid peroxidation (WANG et al., 2020).

NO applied during imbibition of wheat seeds increases the activity of amylases, especially α-amylase, promoting starch degradation and sugar accumulation (SHI et al., 2025). So, it would be expected a positive effect of NO on seed germination, which was not observed on the present study, irrespective of concentration, either applied at ambient or low O_2 (1 kPa) (Figure 3), suggesting that different NO concentrations could be evaluated in each application strategy. Furthermore, unlike the previously mentioned study, the seeds were stored for five months after NO application, which may have suppressed the effect of NO on germination. Refrigeration was efficient, mainly in the absence of atmospheric control, possibly by reducing cellular respiration and oxidative deterioration, contributing to the seed aging reduction (LI et al., 2026).

Vigor (First Count)

The first count showed that, at ambient temperature, treatments with MA and CA (with 50 kPa CO_2 or 1 kPa O_2 + 50 kPa CO_2) kept higher the vigor (Figure 4). Under refrigeration (10 ºC), there were no differences between treatments. Reducing the air temperature to 10 ºC favored vigor only in the control and NO (lowest dose), compared to ambient temperature with no effect on NO (highest dose), MA, and CA (Figure 4). This occurs because, under CA and MA conditions, lower O_2 and/or higher CO_2 reduced the respiration and metabolism. This effect contributes to preserving seed viability even without refrigeration (LUDWIG et al., 2021). These results demonstrated that CA effectively reduces aging effects, as low O_2 and high CO_2 limit cellular respiration and; consequently, reduce oxidative damage that compromises germination capacity (BERGHETTI et al., 2026).

In the control and 50 µL L^{-1} NO treatment the seed vigor was lower at ambient temperature

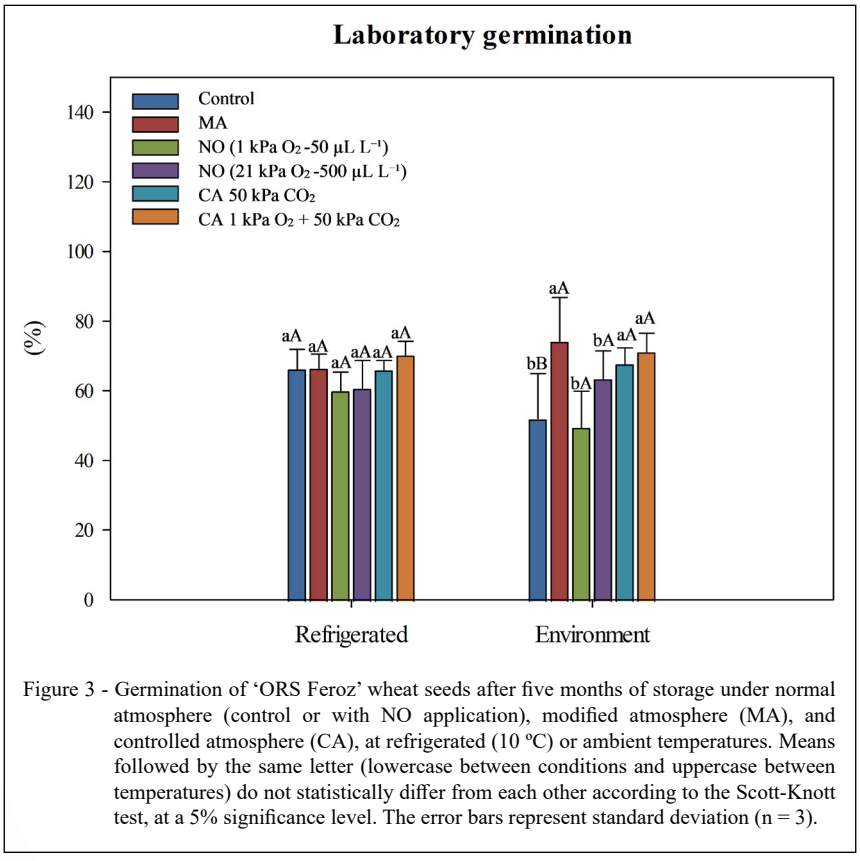


Figure 3 - Germination of 'ORS Feroz' wheat seeds after five months of storage under normal atmosphere (control or with NO application), modified atmosphere (MA), and controlled atmosphere (CA), at refrigerated (10 ºC) or ambient temperatures. Means followed by the same letter (lowercase between conditions and uppercase between temperatures) do not statistically differ from each other according to the Scott-Knott test, at a 5% significance level. The error bars represent standard deviation (n = 3).

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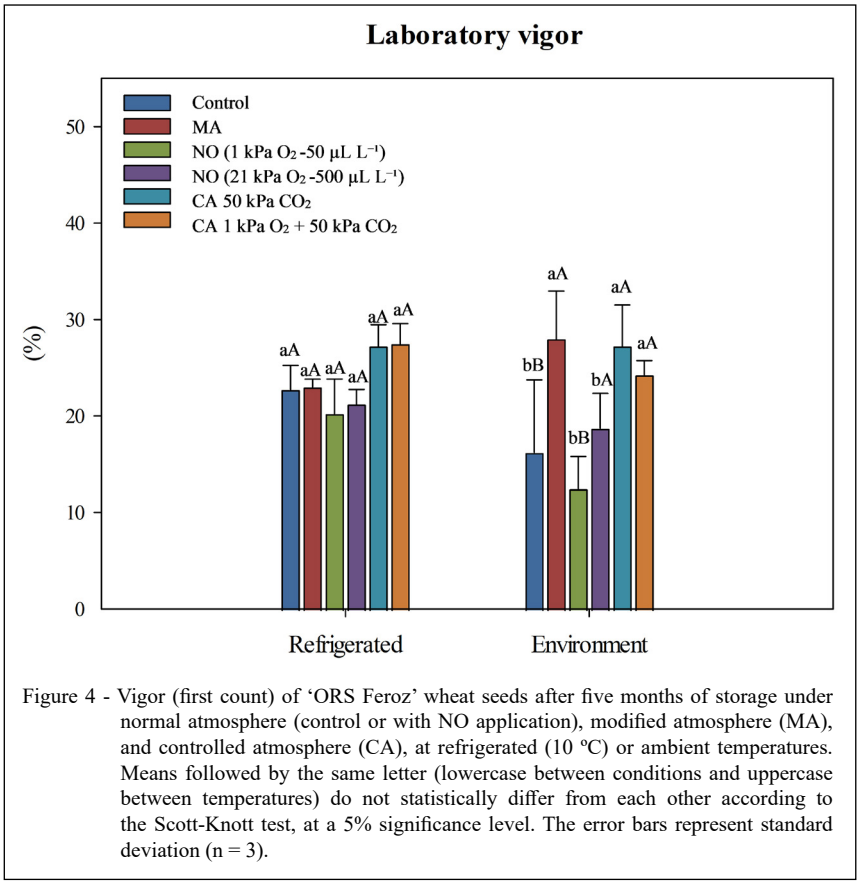


Figure 4 - Vigor (first count) of 'ORS Feroz' wheat seeds after five months of storage under normal atmosphere (control or with NO application), modified atmosphere (MA), and controlled atmosphere (CA), at refrigerated (10 ºC) or ambient temperatures. Means followed by the same letter (lowercase between conditions and uppercase between temperatures) do not statistically differ from each other according to the Scott-Knott test, at a 5% significance level. The error bars represent standard deviation (n = 3).

compared to refrigeration (Figure 4). This low NO concentration did not activate the antioxidant mechanisms, since its effectiveness depends on the concentration and environmental conditions. Low doses of NO, in a non-refrigerated environment, may be ineffective in protection, leading to rapid loss of seed vigor (ROCHA JÚNIOR & USBERTI, 2007).

The low vigor in the control seeds, without temperature or atmosphere management, highlights the importance of refrigeration for maintaining physiological quality. Storage at ambient temperature without additional treatments increases metabolism and ROS production, causing cellular damage, impairing germination and seedling development (LIMA et al., 2006). Seeds treated with higher NO concentration (500 µL L^{-1}) resulted in similar performance between temperatures, although, at ambient temperatures, the vigor was lower than CA and MA-stored ones (Figure 4).

Electrical conductivity

Electrical conductivity (µS cm^{-1} g^{-1}) is widely used to assess the integrity of cell membranes and physiological seeds quality. High values indicate greater electrolyte leakage, resulting in cellular damage and reduced vigor. Mass electrical conductivity test was effective in distinguishing vigor classes in buckwheat seeds, with higher values indicating greater deterioration (ZINI et al., 2024). In the present study, seeds stored at ambient temperature without refrigeration, especially the control and lower dose of NO (50 µL L^{-1}), showed a significant increase in electrical conductivity, indicating greater cellular damage (Figure 5).

This result is associated with the absence of stress mitigation strategies, which exposed the seeds to lipid oxidation and enzymatic degradation, aggravated by the higher temperatures at the experimental site during the storage period (Figure 1). Aged seeds or seeds subjected to adverse conditions accumulate ROS, which promote lipid peroxidation and membrane damage (BEWLEY et al., 2013), which explains the high electrolyte leakage.

NO can activate antioxidant enzymes, such as SOD (superoxide dismutase), POD (peroxidase), and CAT (catalase), resulting in reduced ROS

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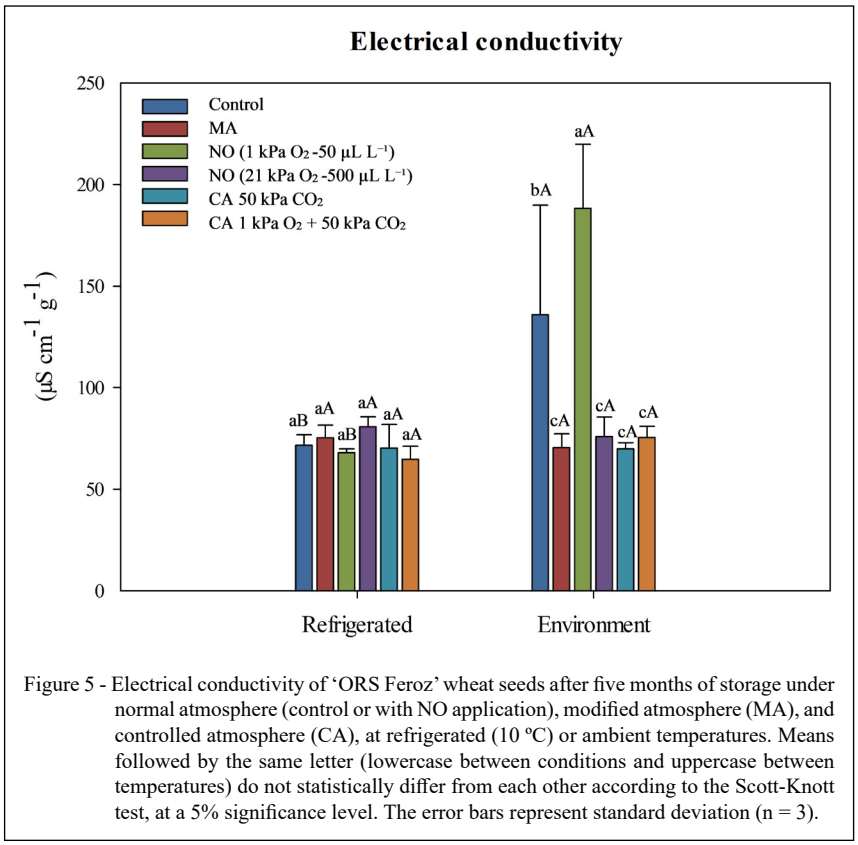


Figure 5 - Electrical conductivity of 'ORS Feroz' wheat seeds after five months of storage under normal atmosphere (control or with NO application), modified atmosphere (MA), and controlled atmosphere (CA), at refrigerated (10 ºC) or ambient temperatures. Means followed by the same letter (lowercase between conditions and uppercase between temperatures) do not statistically differ from each other according to the Scott-Knott test, at a 5% significance level. The error bars represent standard deviation (n = 3).

production and, consequently, in the protection of cell membranes against lipid peroxidation (SHI et al., 2025). The low NO concentration, instead of protecting, favored pro-oxidative reactions, aggravating cellular damage at high temperatures. REN et al. (2020) reported that, at inappropriate concentrations, NO reduces the activity of CAT and ascorbate peroxidase (APX), resulting in increased ROS and malondialdehyde levels, thereby reducing the quality of pakchoi (*Brassica chinensis* L.) seeds and seedlings. Conversely, the application of 500 µL L^{-1} of NO, reduced drastically the electrical conductivity at ambient temperature, compared to the lower NO dose and the control, without differing from MA and CA conditions, indicating better preservation of cellular integrity (Figure 5). This effect can be explained by the biphasic action of NO, in which a suitable concentration induces antioxidant mechanisms and mitigates oxidative stress (PEREIRA et al., 2010). This effect was observed at the present research at the higher NO concentration, even without reducing the O_2 during treatment.

Therefore, the results indicate that seeds stored in CA, MA, and treated with NO in high concentration favor the physiological quality preservation. The CA results are consistent with studies demonstrating that atmospheres with low O_2 concentrations or enriched with CO_2, reduce respiration and ROS production, delaying deterioration (KADER, 2003). These treatments provide more stable storage conditions, resulting in less electrolyte release.

The storage at ambient conditions without any control, whether due to low temperature, gas concentration or the inadequate NO application, compromises the seeds quality. Refrigeration at 10 ºC, however, showed low electrical conductivity values, regardless of storage conditions, demonstrating being an effective strategy for wheat seed storage in southern Brazil, where ambient temperatures are typically higher in this period.

Emergency on seedbeds

Seedling emergence is essential for uniform crops establishment, mainly in wheat crops. Emergence is influenced by environmental factors and storage conditions, which affect seed vigor, germination, and initial seedling survival (BEWLEY

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et al., 2013). No significant differences were observed between storage conditions for emergence in seedbeds at 10 ºC. However, emergence was higher under refrigeration compared to ambient temperature for the control condition and NO application, regardless of the dose, without differences between temperatures for CA and MA conditions. At ambient temperature, the higher emergence in seedbeds were observed under CA, MA, and NO (highest dose), differing significantly from the control and lowest NO dose (Figure 6).

NO at 50 µL L^{-1}, at ambient temperature, resulted in the lowest emergence (< 35%), with no significant difference compared to the control. This indicated that, contrary to expected, the lowest dose of NO did not protect against the deleterious effects of aging and may even intensify oxidative processes. This biphasic effect of NO is described by REN et al. (2020), who highlighted the dependence on dose and tissue sensitivity. NO effectiveness also depends on the synchrony between dose, exposure time, and embryo physiological conditions (RATHER et al., 2020). A noteworthy result is the positive effect of the highest NO dose, even without refrigeration, since the application was carried out without reducing O_2, which is interesting for practical application. The highest concentration of NO may have increased ABA hydroxylase activity in the coleorhiza, resulting in reduced ABA content and thereby promoting coleoptile and radicle emergence (JACOBSEN et al., 2013). In fact, SARATH et al. (2006) reported that the application of SNP, a NO donor, stimulates radicle and coleoptile growth, favoring the establishment of switchgrass (*Panicum virgatum* L.) seedlings.

CA and MA were effective strategies in preserving the vigor of seeds stored at ambient temperature, with emergence similar to that of refrigerated seeds. Both high CO_2 (50 kPa) and the combination of 1 kPa O_2 + 50 kPa CO_2 showed significantly superior results to the control at ambient temperature. Furthermore, the high emergence in the seedbed observed on seeds stored at MA, even at ambient temperature is interesting in practical terms, because its lower implementation costs compared to refrigeration or CA storage.

Additionally, we observed that, in several treatments, field emergence surpassed laboratory germination. In MA under refrigeration, emergence was 80%, compared to 68% germination in the laboratory,

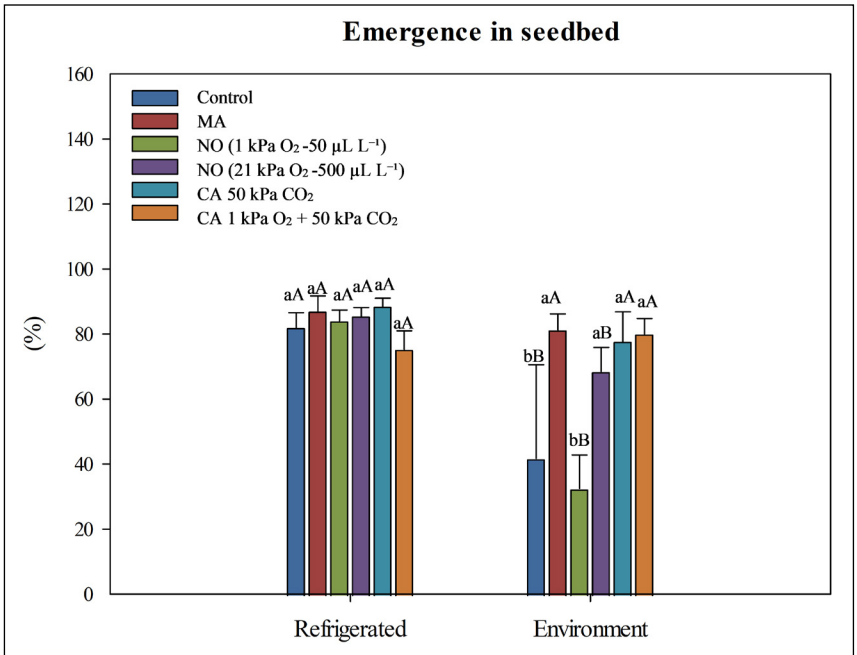


Figure 6 - Emergence in seedbeds of 'ORS Feroz' wheat seeds after five months of storage under normal atmosphere (control or with NO application), modified atmosphere (MA), and controlled atmosphere (CA), at refrigerated (10 ºC) or ambient temperatures. Means followed by the same letter (lowercase between conditions and uppercase between temperatures) do not statistically differ from each other according to the Scott-Knott test, at a 5% significance level. The error bars represent standard deviation (n = 3).

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and in the treatment with 50 kPa CO_2 (10 ºC) emergence was 80% compared to 70% germination in laboratory. This difference can be attributed to the nature of the tests: the laboratory test is more rigorous, counting only normal seedlings, while sowing in the field can allow the emergence of seeds considered abnormal in the laboratory, but with potential to emerge and originate seedlings. This condition represents more faithfully the environment faced by farmers when planting the crop. Conversely, the conditions that resulted in low germination in laboratory tests were apparently even more compromised in the evaluation of germination in seedbeds (control and lower NO concentration, at ambient temperature).

CONCLUSION

Refrigerated storage at 10 ºC maintains the physiological quality of 'ORS Feroz' wheat seeds, preserving membranes integrity, vigor and germination, without the need of additional treatments. In the absence of refrigeration, in the environmental temperature of Southern Brazil, the use of MA is a viable alternative, with good preservation of seed quality and a low-cost strategy. CA is also effective in delaying deterioration; however, greater investment is needed. Overall, there was no difference between the adoption of high CO_2 (50 kPa) alone or association with low O_2 (1 kPa O_2 + 50 kPa CO_2).

Nitric oxide at 500 µL L^{-1}, even applied under normal O_2 conditions (without N_2 flushing), may be a promising technology at ambient temperature, reducing electrical conductivity (membrane permeability) and resulting in higher seed emergence in seedbed. The application of nitric oxide associated with MA or CA storage conditions may be considered in future studies to prolong exposure and maximize the effects of NO on seed quality.

DATA AVAILABILITY STATEMENT

Additional data may be obtained with the corresponding author.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflicts of interest related to this manuscript.

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AUTHORS' CONTRIBUTIONS

The authors contributed equally to the manuscript.

DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE

The authors did not use artificial intelligence to develop the study.

REFERENCES

BERGHETTI, M. R. P et al. The impact of controlled atmosphere storage on maintaining physiological quality and productivity of soybean seeds. **Journal of Stored Products Research**, v.115, p.102868, 2026. Available from: <https://doi.org/10.1016/j.jspr.2025.102868>. Accessed: Jan. 21, 2026. doi: 10.1016/j.jspr.2025.102868.

BEWLEY, J. D. et al. **Seeds**: physiology of development, germination and dormancy. 3. ed. New York: Springer, 2013. 392 p. Available from: <https://doi.org/10.1007/978-1-4614-4693-4>. Accessed: May, 01, 2025. doi: 10.1007/978-1-4614-4693-4.

BRACKMANN, A. et al. Controlled atmosphere storage conditions for 'Pink Lady' apples. **Ciência Rural**, v.35, n.3, p.504–509, 2005. Available from: <https://doi.org/10.1590/S0103-84782005000300003>. Accessed: Apr. 13, 2025. doi: 10.1590/S0103-84782005000300003.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. **Regras para análise de sementes**. Brasília, DF: Secretaria de Defesa Agropecuária, 2009. 307–316 p.

BRUM, A. L.; HECK, C. R. A economia do trigo no Rio Grande do Sul: breve histórico do cereal na economia do Estado. Análise – **Revista de Administração da PUCRS**, v.16, n.1, p.29-44, 2005. Available from: <https://revistaseletronicas.pucrs.br/face/article/view/263>. Accessed: Apr. 1, 2025.

CASTRO, R. L. de et al. Wheat crop in the state of Rio Grande do Sul, Brazil, 2018. **Annual Wheat Newsletter**, v.66, p.8, 2018. Available from: <https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/1124945/1/AWN-VOL-66-p8-11pdf.pdf>. Accessed: Apr. 13, 2025.

CIACKA, K. et al. Nitric oxide - an antidote to seed aging modifies meta-tyrosine level and expression of genes encoding antioxidant proteins in apple embryos. **Frontiers in Plant Science**, v.13, 2022. Available from: <https://doi.org/10.3389/fpls.2022.929245>. Accessed: Apr. 21, 2025. doi:10.3389/fpls.2022.929245.

CONAB, Companhia Nacional de Abastecimento. **Produção de grãos 2024/25 é estimada em 322,3 milhões de toneladas, com clima favorável para as culturas de 1ª safra**. Brasília, 26 jun. 2025. Available from: <https://www.gov.br/conab/pt-br/atuacao/informacoes-agropecuarias/safras/safra-de-graos/8o-levantamento-safra-2024-25/boletim-da-safra-de-graos>. Accessed: Jul. 06, 2025.

DEVILLA, I. A. et al. Variations of temperature and moisture content of grains stored in bins with aeration. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.8, n.2/3, p.284–291, 2004. Available from:

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20250121

<https://doi.org/10.1590/S1415-43662004000200018>. Accessed: May, 30, 2025. doi: 10.1590/S1415-43662004000200018.

FERREIRA, D. F. SISVAR: a computer analysis system to fixed effects split plot type designs. **Revista Brasileira de Biometria**, v.37, n.4, p.529–535, 2019. Available from: <https://doi.org/10.28951/rbb.v37i4.450>. Accessed: Jul. 6, 2025. doi: 10.28951/rbb.v37i4.450.

KADER, A. A. A perspective on postharvest horticulture (1978–2003). **HortScience**, v.38, n.5, p.1004–1008, 2003. Available from: <https://doi.org/10.21273/HORTSCI.38.5.1004>. Accessed: May, 03, 2025. doi: 10.21273/HORTSCI.38.5.1004.

JACOBSEN, J. V. et al. Roles for blue light, jasmonate and nitric oxide in the regulation of dormancy and germination in wheat grain (*Triticum aestivum* L.). **Planta**, v.238, p.121-138, 2013. Available from: <https://doi.org/10.1007/s00425-013-1878-0>. Accessed: May, 20, 2026. doi: 10.1007/s00425-013-1878-0.

KUMAR, P. et al. A review on seed storage technology: recent trends and advances in sustainable techniques for global food security. **AgroEnvironmental Sustainability**, v.2, n.1, p.34–50, 2024. Available from: <https://doi.org/10.59983/s2024020105>. Accessed: Apr. 30, 2025. doi: 10.59983/s2024020105.

LI, Y. et al. Temperature-dependent fungal diversity, storage quality, and processing quality of high-moisture wheat during post-harvest storage. **Foods**, v.15, n.361, 2026. Available from: <https://doi.org/10.3390/foods15020361>. Accessed: May, 19, 2026. doi: 10.3390/foods15020361.

LIMA, T. C. et al. Vigor evaluation of wheat seeds using the accelerated aging test. **Revista Brasileira de Sementes**, v.28, n.1, p.106-113, 2006. Available from: <https://doi.org/10.1590/S0101-31222006000100015>. Accessed: May, 09, 2025. doi: 10.1590/S0101-31222006000100015.

LUDWIG, V. et al. Impact of controlled atmosphere storage on physiological quality of soybean seed. **Journal of Stored Products Research**, v.90, p.101749, 2021. Available from: <https://doi.org/10.1016/j.jspr.2020.101749>. Accessed: Jul. 06, 2025. doi: 10.1016/j.jspr.2020.101749.

MARCOS FILHO, J. **Fisiologia de sementes de plantas cultivadas**. Piracicaba: FEALQ. 2005. p. 495.

NITHYA, U. et al. Safe storage guidelines for durum wheat. **Journal of Stored Products Research**, v.47, p.328-333, 2011. Available from: <https://doi.org/10.1016/j.jspr.2011.05.005>. Accessed: May, 19, 2026. doi: 10.1016/j.jspr.2011.05.005.

PEREIRA, B. L. C. et al. Influence of nitric oxide on the germination of seeds of *Plathymenia reticulata* Benth with low vigor. **Scientia Forestalis**, v.38, n.88, p.629–636, 2010. Available from: <https://www.ipef.br/publicacoes/scientia/nr88/cap09.pdf>. Accessed: May, 1, 2025.

PIRES, R. M. O. et al. Protective action of nitric oxide in sesame seeds submitted to water stress. **Journal of Seed Science**, v.38, n.4, p.350–357, 2016. Available from: <https://doi.org/10.1590/2317-1545v38n4166972>. Accessed: Jul. 31, 2025. doi: 10.1590/2317-1545v38n4166972.

RATHER, B. A. et al. Nitric oxide pre-treatment advances seed germination and alleviates copper-induced photosynthetic inhibition in Indian mustard. **Plants**, v.9, n.6, p.776, 2020. Available from: <https://doi.org/10.3390/plants9060776>. Accessed: May, 02, 2025. doi: 10.3390/plants9060776.

REN, Y. et al. Nitric oxide alleviates salt stress in seed germination and early seedling growth of pakchoi (*Brassica chinensis* L.) by enhancing physiological and biochemical parameters. **Ecotoxicology and Environmental Safety**, v.187, 109785, 2020. Available from: <https://doi.org/10.1016/j.ecoenv.2019.109785>. Accessed: May, 21, 2026. doi: 10.1016/j.ecoenv.2019.109785.

RIBEIRO, G. et al. Stress for high temperatures in wheat: impact on development and mechanisms of tolerance. **Revista Brasileira de Agrociência**, v.18, n.2-4, p.133–142, 2012a. Available from: <https://periodicos.ufpel.edu.br/index.php/CAST/article/view/2502>. Accessed: Apr. 13, 2025.

RIBEIRO, M. S. et al. Storage of palm tree seeds under modified atmosphere conditions. **Bragantia**, v.71, n.3, p.349–356, 2012b. Available from: <https://doi.org/10.1590/S0006-87052010000400026>. Accessed: Apr. 02, 2025. doi: 10.1590/S0006-87052010000400026.

ROCHA JÚNIOR, L. S.; USBERTI, R. Physical and physiological quality of open-stored wheat seeds after phosphine application. **Revista Brasileira de Sementes**, v.29, n.1, p.45–51, 2007. Available from: <https://doi.org/10.1590/S0101-31222007000100007>. Accessed: May, 09, 2025. doi: 10.1590/S0101-31222007000100007.

SARATH, G. et al. Nitric oxide accelerates seed germination in warm-season grasses. **Planta**, v.223, p.1154-1164, 2006. Available from: <https://doi.org/10.1007/s00425-005-0162-3>. Accessed: May, 20, 2026. doi: 10.1007/s00425-005-0162-3.

SCARIOT, M. A. et al. Physiological performance of wheat seeds as a function of moisture content at harvest and storage system. **Pesquisa Agropecuária Tropical**, v.47, n.4, p.456–464, 2018. Available from: <http://dx.doi.org/10.1590/1983-40632017v4749550>. Accessed: Apr. 01, 2025. doi: 10.1590/1983-40632017v4749550.

SHI, S. et al. Exogenous nitric oxide relieves iron-inhibitory effect on wheat seed germination. **Ecotoxicology and Environmental Safety**, v.291, 11785, 2025. Available from: <https://doi.org/10.1016/j.ecoenv.2025.117875>. Accessed: May, 21, 2026. doi: 10.1016/j.ecoenv.2025.117875.

ZINI, P. B. et al. Mass Electrical conductivity test in determining the prediction of buckwheat seed lots. **Ensaios e Ciência: Ciências Biológicas, Agrárias e da Saúde**, v.28, n.2, p.169–175, 2024. Available from: <https://doi.org/10.17921/1415-6938.2024v28n2p169-175>. Accessed: Apr. 30, 2025. doi: 10.17921/1415-6938.2024v28n2p169-175.

WANG, R. et al. Effects of deterioration and mildewing on the quality of wheat seeds with different moisture contents during storage. **RSC Advances**, v.10, p.14581–14594, 2020. Available from: <https://doi.org/10.1039/D0RA00542H>. Accessed: Jul. 6, 2025. doi: 10.1039/D0RA00542H.

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