2026 International Nuclear Atlantic Conference – INAC 2026
Escola de Guerra Naval, Rio de Janeiro, RJ, August 24 - 28, 2026

Radiation-induced hormesis in high-water activity seeds: preserving the germination potential of *Protium heptaphyllum* during storage

Barreira. Daili[1], Barros, João. P. A. A[1],
Reis-Rodrigues.Priscila[1,] and
Villavicencio, Anna Lucia C.H[1]

[1] *daili_andrade@usp.br, Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN)Prof. Lineu Prestes Ave, 2242 - Cidade Universitária05508-000, São Paulo, SP, Brazil*

1. Introduction

The conservation of native forest species, such as *Protium heptaphyllum* (PH), faces the critical challenge of the short longevity of its recalcitrant seeds, which rapidly lose viability due to high metabolism and sensitivity to desiccation. Traditionally, ionizing radiation has been associated with mutagenesis; however, recent advances indicate its potential as a physical priming agent to improve vigor and physiological stability. In seeds with high water activity (a.w) controlled doses of gamma radiation can modulate the oxidative status, stimulating cellular repair mechanisms that, theoretically, could extend the storage window. This study investigates the ionizing radiation threshold in PH seeds, focusing on maintaining viability and stimulating germination as a technological innovation strategy for seedling production and germplasm conservation. The concept of radiation hormesis is based on the hypothesis that low doses of ionizing radiation can trigger positive biological responses, increasing the resilience of plant tissues to subsequent stresses. According to Luckey (1980), in his seminal work on hormesis, low-intensity stimuli can optimize vital functions, including germination rate and seedling vigor. For recalcitrant seeds, where metabolism is not interrupted, gamma radiation interacts with the intraembryonic water matrix to generate molecular signals that activate antioxidant enzymes. Thus, the use of nuclear technology for "vigor enhancement" represents a paradigm shift, aiming not at genetic alteration, but at improving physiological performance and extending the lifespan of seeds that would otherwise be lost within a few days.

2. Methodology

The fruits of Protium heptaphyllum were collected in September 2025 in the Tupinambá Indigenous Village of Olivença, Una, Bahia (~ 15° 00′ 06″ S, 39° 00′ 04″ W), following the morphological criteria of Lorenzi (2008) and the precepts of Law No. 13.123/2015 . The seeds (length ≥ 41 mm; weight 7.40 ± 0.70 g) were irradiated at SETER-IPEN (GammaCell) at doses of 0, 100, 200 and 300 Gy. The thermodynamic status of intraembryonic water was characterized via water activity (w.a) using an AquaLab 4TE hygrometer at 25 °C immediately before irradiation, revealing an average initial moisture content of 97.8%. This procedure ensured accuracy in assessing the water status at the exact moment of radiative interaction, a determining factor for the physiological response.

The experimental design evaluated viability at three dry storage intervals (0, 10, and 15 days). Before each germination test, the seeds were pre-soaked in distilled water for 6 hours to ensure uniform hydration. The trials were conducted in a germinex system for 30 days, using 20 seeds per treatment in each evaluated period. This protocol was designed to test the ability of ionizing radiation to preserve seed viability under storage stress, seeking to identify whether the applied doses could mitigate the natural decline in vigor observed in recalcitrant species.

3. Results and Discussion

Analysis of water activity revealed a complex dynamic between radiation doses and storage time, highlighting how ionizing radiation influences the thermodynamic status of water. On day 0, all doses showed high (a.w), ranging from 98.0% to 99.0%, indicating a state of maximum free energy at the time of irradiation (Table I).

Table I: Mean and standard deviation of water activity (w.a) by storage period.

Dose	Day 0 (%)	Day 10 (%)	Day 15 (%)
Control	98.0	68.6	56.4
100 Gy	99.0	62.5	45.5
200 Gy	98.0	78.3	52.5
300 Gy	98.0	50.5	40.0

One-way ANOVA revealed a highly significant effect of storage time on germination percentage ($F(2, 9) = 40.66$, $p < 0.001$), whereas the radiation dose did not significantly influence the results ($F(3, 8) = 0.16$, $p = 0.919$\$). Follow-up t-tests indicated a significant reduction in germination between day 0 and day 10 ($p = 0.0012$), and a highly significant drop by day 15 ($p < 0.0001$). The decrease between day 10 and day 15, however, did not reach statistical significance ($p = 0.0544$).

However, throughout storage, the 200 Gy dose showed the highest (w.a) retention at 10 days (78.3%) and at 15 days (52.5%) compared to the control and other doses. In contrast, the 300 Gy dose resulted in the lowest final (w.a) (40.0%), suggesting that high doses may accelerate the degradation of cellular structures responsible for water retention in recalcitrant seeds. Water activity should be interpreted as the chemical potential that governs molecular mobility and the reactivity of free radicals induced by gamma radiation (PAMMENTER; BERJAK, 2014).

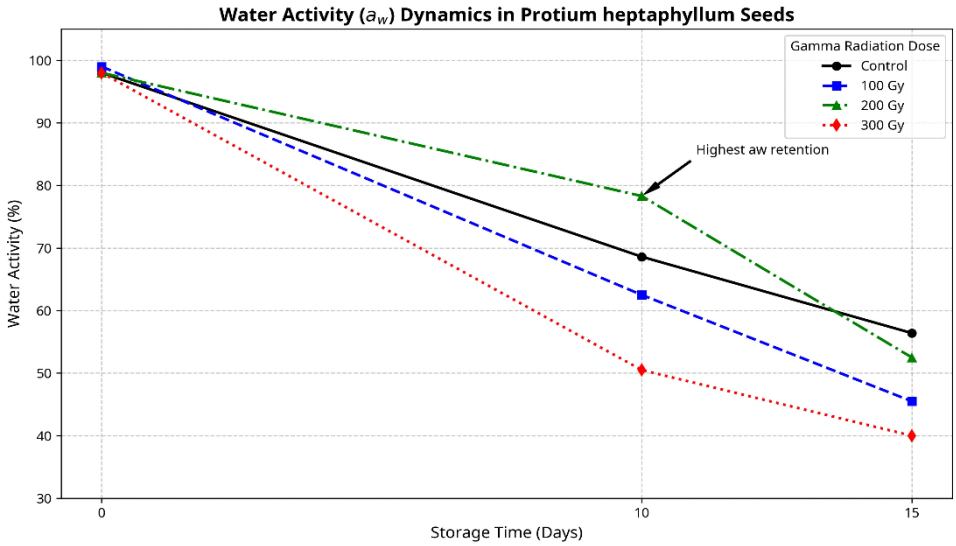
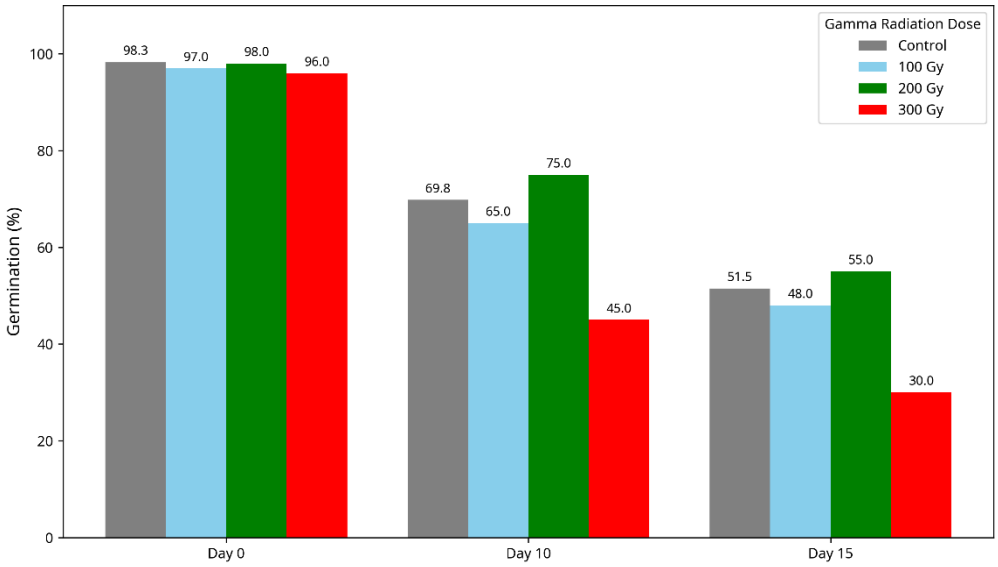


Figure 1: Graph of dynamics of water activity (w.a) in the irradiated seeds of *Protium heptaphyllum*.

The correlation between water activity and viability demonstrates that the 200 Gy dose acted as a vigor agent, maintaining water activity at higher levels during critical storage. This effect can be attributed to "physical priming," where gamma radiation stimulates the synthesis of protective proteins that stabilize cell membranes against desiccation. As discussed by Pammenter and Berjak (2014), maintaining viability in recalcitrant organisms depends on mitigating oxidative stress and water collapse. The fact that the 200 Gy dose preserved a w.a. of 52.5% at 15 days suggests greater metabolic resilience compared to the 300 Gy dose, which reached a threshold of 40.0%, correlating with the accelerated loss of germination capacity.

The data obtained suggest that gamma radiation can be integrated into ex situ conservation protocols, assisting in maintaining viability during the transport and temporary storage of forest seeds of high ecological value.

Figure 2: Graph of Germination percentage of Protium heptaphyllum seeds subjected to gamma radiation doses over 15 days of storage.



Dose of 200 Gy (green): Confirmed as the best performing dose, even surpassing the control on days 10 and 15, illustrating the priming effect and the greater water activity retention discussed earlier. Dose of 300 Gy (red): shows the most drastic decline in germination, falling to 30% on day 15, which is directly correlated with the loss of thermodynamic water status. Dose of 100 Gy (blue): shows stable behavior, but with slightly lower vigor than the 200 Gy dose.

Technological innovation in the production of viable *P. heptaphyllum* seeds requires optimizing the radiation dose so that it acts as a biostimulant. The fact that the seeds germinated after irradiation and storage proves that it is possible to produce viable batches using nuclear techniques. Integrating this practice with precise measurement of water activity allows for unprecedented quality control. Instead of seeking changes in DNA, the technique focuses on "awakening" the seed's defense metabolism, preparing it to better resist damage caused by the inevitable loss of water during handling. This opens doors for the large-scale use of radiation in forest nurseries, ensuring a higher rate of seedling establishment in the field.

4. Conclusions

This study demonstrates that ionizing radiation is a promising tool for improving the vigor and conservation of recalcitrant *Protium heptaphyllum* seeds. Gamma radiation application in doses up to 200 Gy, positively affects the maintenance of water activity and vigor in recalcitrant *Protium heptaphyllum* seeds. The observed water dynamics reveal that controlled doses can delay the decline of water free energy during storage, favoring the production of viable seeds that germinate effectively. The 300 Gy threshold was identified as detrimental, accelerating the loss of water activity and compromising physiological integrity. Therefore, monitoring water activity is a sensitive and necessary indicator to validate the effectiveness of radioactive treatments in sensitive forest species.

It concludes that the identified radiation threshold allows for the maintenance of germination capacity even after critical periods of dry storage, consolidating the technique as an effective method for the post-harvest management of this native species. For the storage of recalcitrant seeds, radiation acts as a vigor agent that helps stabilize embryonic metabolism under water stress conditions. The adoption of low-dose irradiation protocols is recommended as part of a large-scale seedling production strategy, aiming not only at quantity but also at the quality and longevity of the propagative material. Thus, nuclear technology establishes itself as an essential pillar for food security and environmental restoration, guaranteeing the availability of viable seeds of strategic forest species.

Acknowledgements

This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel (CAPES) and the Institute for Energy and Nuclear Research (IPEN/CNEN), Brazil.

References

[1] LUCKEY, T. D., Hormesis with Ionizing Radiation, *CRC Press*, Boca Raton, FL (1980).
[2] LORENZI, H., Árvores Brasileiras: Manual de identificação e cultivo de plantas arbóreas nativas do Brasil, Instituto Plantarum, Nova Odessa, SP (2008).
[3] PAMMENTER, N. W.; BERJAK, P., "Physiology of desiccation-sensitive (recalcitrant) seeds and the implications for cryopreservation," *Int. J. Plant Sci.*, vol. 175, pp. 21–28 (2014).
[4] ROBERTS, E. H., "Predicting the viability of seeds," Seed Science and Technology, vol. 1, pp. 499–514 (1973).
[5] MARCU, D. et al., "Gamma radiation effects on seed germination, growth and pigment content, and ESR study of free radicals in wheat," *Braz. J. Plant Physiol.*, vol. 25, pp. 103–114 (2013).