Truta P *et al.* (2025)
Notulae Botanicae Horti Agrobotanici Cluj-Napoca
Volume 53, Issue 4, Article number 14811
DOI:10.15835/nbha53414811
Research Article

Reproductive trait variability and seed germination responses to electric field and low-dose gamma irradiation in *Larix decidua* Mill.

Petru TRUTA[1,2], Irina M. MORAR[1,3*], Alina M. TRUTA[1*], Catalina DAN[4], Oana VIMAN[1], Iulia Diana ARION[1,3], Florin IORAS[5], Adriana F. SESTRAS[1], Leontin DAVID[2]

[1]*University of Agricultural Sciences and Veterinary Medicine, Faculty of Forestry and Cadastre, Department of Forestry, 400372 Cluj-Napoca, Romania; petru.truta@usamvcluj.ro; irina.todea@usamvcluj.ro (*corresponding author); alina.truta@usamvcluj.ro (*corresponding author); oana.viman@usamvcluj.ro; iulia.gliga@usamvcluj.ro; adriana.sestras@usamvcluj.ro*
[2]*Babes-Bolyai University, Physics Department, Cluj-Napoca, Romania; petru.truta@usamvcluj.ro; leontin.david@ubbcluj.ro*
[3]*Academy of Romanian Scientists, Ilfov 3, 050044 Bucharest, Romania*
[4]*University of Agricultural Sciences and Veterinary Medicine, Faculty of Horticulture and Business in Rural Development, Department of Horticulture and Landscape, 400372 Cluj-Napoca, Romania; catalina.dan@usamvcluj.ro*
[5]*Research and Enterprise Directorate, Buckinghamshire New University, High Wycombe HP11 2JZ, UK; florin.ioras2@bucks.ac.uk*

Abstract

Larix decidua Mill. (European larch) is an ecologically and economically important deciduous conifer in European mountain ecosystems, whose regeneration success depends on reproductive trait variability and seed physiological quality. Under ongoing climate change, understanding provenance-related differences and identifying effective, environmentally safe pre-sowing treatments are increasingly important. This study assessed the phenotypic variability of cones and seeds across seven geographic provenances of *L. decidua* established in the Baciu seed orchard (Romania) and evaluated seed germination responses to physical stimulation using electric field exposure and low-dose gamma irradiation. Significant differences among provenances were observed for cone morphology and seed biometric traits, including seed weight, size, and number of seeds per cone. Provenances from Sinaia and Brașov V.P. exhibited the highest mean seed weights, while Brașov V.C. produced lighter seeds. Germination experiments showed that electric field treatments significantly enhanced germination, with higher voltages and longer exposure times producing the strongest effects. Low-dose gamma irradiation induced a clear dose-dependent response, with the 2 Gy treatment consistently improving germination percentage, germination index, and early seedling vigor across most provenances. Multivariate analyses (canonical correspondence analysis and UPGMA clustering) revealed distinct provenance-specific physiological responses, with Anina and Sinaia showing divergent reaction patterns, while Gura Humorului, Brașov V.C. and Brașov V.P. formed a more homogeneous group. The results indicate that reproductive trait variability and seed germination capacity in *L. decidua* are strongly influenced by provenance origin and can be effectively modulated by physical pre-sowing treatments, supporting their use in regeneration programs.

Keywords: climate adaptation; electric field; genetic resources; seed germination; γ rays' treatments

Received: 14 Oct 2025. Received in revised form: 19 Dec 2025. Accepted: 20 Dec 2025. Published online: 23 Dec 2025.
From Volume 49, Issue 1, 2021, Notulae Botanicae Horti Agrobotanici Cluj-Napoca journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

Introduction

Climate change represents one of the most pressing challenges for forest ecosystems globally, with coniferous forests being particularly vulnerable to shifting temperature and precipitation patterns (Ahirvar *et al.*, 2020; Wu *et al.*, 2022; Kabir *et al.*, 2023). Various abiotic stressors, including soil salinity, temperature fluctuations, drought, and soil degradation through erosion, significantly affect plant growth and species distribution in natural ecosystems (Camarero *et al.*, 2024). Soil erosion, recognized as one of the most wide-spread forms of land degradation globally, can lead to constrained root development, diminished water availability, decreased soil fertility, and altered nutrient dynamics factors that are particularly detrimental during the critical early stages of seedling establishment (Tiebel and Karge, 2025). This highlights the critical protective role of healthy forests, which deliver a multitude of indispensable ecosystem services. Beyond their economic value, forests are vital climate regulators through carbon sequestration, protect water resources and soil stability, purify the air, and sustain biodiversity as well as cultural landscapes (Thompson *et al.*, 2009; Cairns and Meganck, 1994; Sestras *et al.*, 2018; Curovic *et al.*, 2020; Hernández-Blanco *et al.*, 2022; Liu *et al.*, 2024). Temperature stress, in particular, can hinder seedling growth, especially during the early stages of plants' development. Considering these factors, coniferous forests are regarded as particularly vulnerable ecosystems to the effects of climate change (Kurz *et al.*, 2008; Roshani *et al.*, 2022). Understanding how tree species respond to these environmental pressures is useful for developing adaptive management strategies (Chan *et al.*, 2016; Baldrian *et al.*, 2023).

Recent research on Romanian forest species, including those in central and eastern Romania, has revealed significant vulnerability to anticipated climate change scenarios (Crisan *et al.*, 2022; Morar *et al.*, 2023), highlighting the necessity for species-specific assessments and adaptive management strategies across all major forest taxa, including vulnerable conifers like European larch.

Larix decidua Mill. (European larch) is an ecologically and economically important coniferous species native to the mountainous regions of Central Europe (Pàques *et al.*, 2013; Vilcan *et al.*, 2013; Kempf *et al.*, 2023). European larch exhibits a discontinuous distribution across the mountain regions of southern, central, and eastern Europe, extending from southeastern France and southwestern Italy, to eastern Poland and central Romania (Albert *et al.*, 2008; Farcas *et al.*, 2013; Wagner, *et al.*, 2015). The species occupies a wide altitudinal gradient, forming continuous forests from approximately 180 m in Poland up to about 2,500 m in the central and southwestern Alps (Milad *et al.*, 2011; Vilcan (Truta) *et al.*, 2017; Teodosiu *et al.*, 2023). At the upper limits of its range, European larch may persist as scattered groups or solitary individuals, particularly in sheltered microsites that mitigate extreme abiotic stress.

Unlike most conifers, *L. decidua* is deciduous, shedding its needles annually, which provides unique adaptations to cold climates and seasonal resource limitations (Tiebel and Karge, 2025). This species is valued for its wood, which is durable and highly sought after in construction, as well as for its ecological contributions to forest ecosystems (Kogelnig-Mayer *et al.*, 2013; Hammond *et al.*, 2022). European larch plays a fundamental role in forest regeneration, soil stabilization, and supporting biodiversity. Similar to silver fir (*Abies alba*), European larch is also affected by the increasing climate change pressures (Zhou *et al.*, 2019; Morar *et al.*, 2023). Larch is widely recognized for its cold climate tolerance, providing it with an advantage in higher altitudes and northern latitudes. However, like other conifer species, it faces challenges from rising temperatures, altered precipitation patterns, and droughts, which can reduce its growth and survival rates. Thus, despite its cold tolerance and wide ecological amplitude, *L. decidua* faces increasing pressures from climate change, particularly regarding altered temperature regimes and water availability (Dobrowolska *et al.*, 2017).

Genetic diversity within forest tree populations is fundamental for adaptation to changing environmental conditions (Mihai and Teodosiu, 2018; Alotaibi *et al.*, 2023). Phenotypic variability in reproductive traits, such as cones and seed characteristics, reflects both genetic differentiation and local adaptation to specific ecological conditions (Vilcan *et al.*, 2013; Mihai *et al.*, 2019). Studies on seed morphology and cone characteristics provide insights into reproductive strategies, dispersal potential and regeneration success across different environments (Roman *et al.*, 2022a; Arion *et al.*, 2024).

An important factor in preserving and expanding forest ecosystems is the seed germination process, which represents the initial stage of the plant life cycle, where the embryo exits dormancy and initiates active growth. Germination is thus an important phase for plant establishment, as it marks the beginning of a new generation and constitutes a period of high vulnerability for the developing seedling (Choi *et al.*, 2009; Todea *et al.*, 2020). *L. decidua* germination is influenced by a range of internal factors (such as seed viability and nutrient reserves), as well as external conditions (including temperature, moisture, light, and the presence of stimulatory or inhibitory substances).

In the context of climate change and modern silvicultural interventions, understanding the germination process of *L. decidua* and assessing the effects of pre-sowing treatments are increasingly important aspects for improving regeneration efficiency and ensuring the conservation of this valuable species (Li *et al.*, 2021). For larch, elucidating provenance specific variation in cones and seed traits, together with germination behavior, is essential for identifying superior genetic material for reforestation programs and predicting how populations may respond to future climatic scenarios.

Provenance trials, which test the performance of populations from different geographic origins under common environmental conditions, are powerful tools for assessing genetic variation and identifying adapted seed sources (Schiop *et al.*, 2017; Todea *et al.*, 2020; Ciocirlan *et al.*, 2021). The Baciu orchard, established with clonal material from seven natural and artificial *L. decidua* populations across Romania, provides a unique opportunity to evaluate phenotypic variation in cones and seed characteristics, while also considering environmental effects (Plesa *et al.*, 2019; Vilcan (Truta) *et al.*, 2017). Such comparative studies are particularly valuable for species like *L. decidua*, for which research in Romania has been limited compared to other European countries.

As germination is a significant part of the future development of a valuable population as mentioned above, and considering the possibilities to secure optimal results, different approaches were considered. One of the most important physical factors that can be applied in seed treatment and germination enhancement is the electric field (Yang and Shen, 2011; Pauzaite *et al.*, 2018; Čėsnienė *et al*, 2023). Germination experiments conducted under different electric current intensities aimed to assess the influence of electrostimulation on seed viability and early germination dynamics, providing new insights into potential methods for improving propagation efficiency and seedling performance (Yang and Shen, 2011; Yudaev *et al.*, 2023). According to Sudsiri *et al.* (2017), electric fields (EF) can enhance not only germination speed, but also final germination percentage, effects that are now being investigated in forestry species of high ecological and economic relevance. Yudaev *et al.* (2023) emphasized that the use of electric treatments in plant production offers several advantages, including low toxicity and minimal surface or groundwater contamination, which in turn contributes to reducing overall production costs in forest nursery systems.

Given the limited information available on the effects of γ-ray treatments on seeds, the present study aimed to evaluate also the influence of low-dose gamma irradiation on the germination of European larch (*L. decidua*) seeds. Gamma irradiation (γ-rays) is one of the most widely used methods for inducing genetic variation in numerous plant species (El-Shakhs *et al.*, 2007; De Micco *et al.*, 2011), including forest trees (Iglesias-Andreu *et al.*, 2012; Geng *et al.*, 2019) and various plant organs. Research on γ-irradiation has also been applied to delay fruit ripening (World Organization of Health and Nutrition in Agriculture, United Nations, 1988), reduce bacterial loads, fungi, insects, and other pathogenic contaminants (Blagojevic *et al.*, 2019; De Rouck, *et al.*, 2025), or improve seed storability (Villegas *et al.*, 2023). Low-dose γ-ray treatments have been reported to stimulate seed germination and increase fruit number and overall yield by up to 86% (Sheppard *et al.*, 1992). Gamma rays can significantly influence seedling growth and development through genetic, cytological, biochemical, and physiological changes (Kiong *et al.*, 2008), as well as through morphogenetic modifications in cells and tissues, closely linked to the irradiation dose (Blagojevic *et al.*, 2019). Although normally the seed already contains the materials and energy needed for initial growth, certain stimulatory factors are required or beneficial to activate the substances stored in the cotyledons. Low doses of γ-rays may activate enzymes and stimulate the young embryo, enhancing cell division and influencing not only germination, but also the vegetative growth (Piri *et al.*, 2011; Holonec *et al.*, 2021). The biological effects of γ-rays are primarily attributed to the formation of free radicals resulting from water radiolysis, which can modulate the antioxidant system and lead to the accumulation of phenolic compounds and chlorophyll pigments (Wi *et al.*, 2006; Geras'kin *et al.*, 2011; Kondrateva *et al.*, 2019).

Despite the potential of γ-rays to enhance germination performance, relatively few studies have examined their effects on tree species (Iglesias-Andreu *et al.*, 2012). Most forestry research on seed germination has relied on conventional physical or chemical pre-sowing treatments, while low-dose γ-irradiation has been used mainly to generate variation for breeding purposes through induced mutations. It is well established that plant responses to γ-irradiation depend on several factors, including radiation dose, species or genotype, and the specific plant organ under investigation (Esnault *et al.*, 2010; De Micco *et al.*, 2011).

The main objectives of this study were to assess the morphological diversity of cones and seed traits across seven *L. decidua* provenances from the Baciu seed orchard and to determine how these traits relate to germination performance under electric current stimulation and γ-ray treatments. Furthermore, the study aimed to identify provenances exhibiting enhanced reproductive or physiological responses, which may reflect greater fitness or adaptive potential information that is valuable for forest genetic resource management, breeding efforts and climate change adaptation strategies. Maintaining provenance level diversity is fundamental not only for species conservation, but also for maintaining the multiple ecosystem services provided by mountain forests (Arion *et al.*, 2023). By documenting phenotypic variability in key reproductive traits and linking it with germination responses under controlled enhancement treatments, this research supports the conservation and sustainable use of *L. decidua* genetic resources in Romania and Central Europe (Vilcan *et al.*, 2013; Vilcan (Truta) *et al.*, 2017; Gramazio *et al.*, 2018).

In this context, the present study seeks to clarify how electric fields and low-dose γ-irradiation affect seed germination in European larch, offering new insights that may improve nursery practices and strengthen regeneration strategies for this ecologically and economically important forest species.

Materials and Methods

Geographical distribution of the provenances

In this study, the biological material consisted of vegetative clones of *Larix decidua* together with the stands from which these clones originated. The clones were produced within a breeding program through the selection of superior individuals from various Romanian geographical regions, belonging to natural or artificial populations: Gura Humorului, Brașov V.C., Săcele, Brașov V. P and Sinaia located in northern Romania, as well as Anina and Latorița situated in the southern part of the country (Figure 1). Plus trees serving as sources of scions were identified within these provenance populations.

The vegetative shoots were grafted onto a uniform rootstock seedling of European larch, resulting in clones, which formed the baseline experimental biological material. These clones were established in the Baciu seed orchard in 1975. The orchard is positioned at 46°8′ N latitude and 23°52′ E longitude, at an average elevation of 357 m a.s.l. Cones for the present investigation were collected from mature trees (50 years old). For each provenance, cones were harvested from multiple plus trees, to ensure a representative sampling of genetic variation within each origin population. Larch cones were stored indoors for drying, at temperatures of 20-25 °C and the seeds were manually extracted from the dried cones.

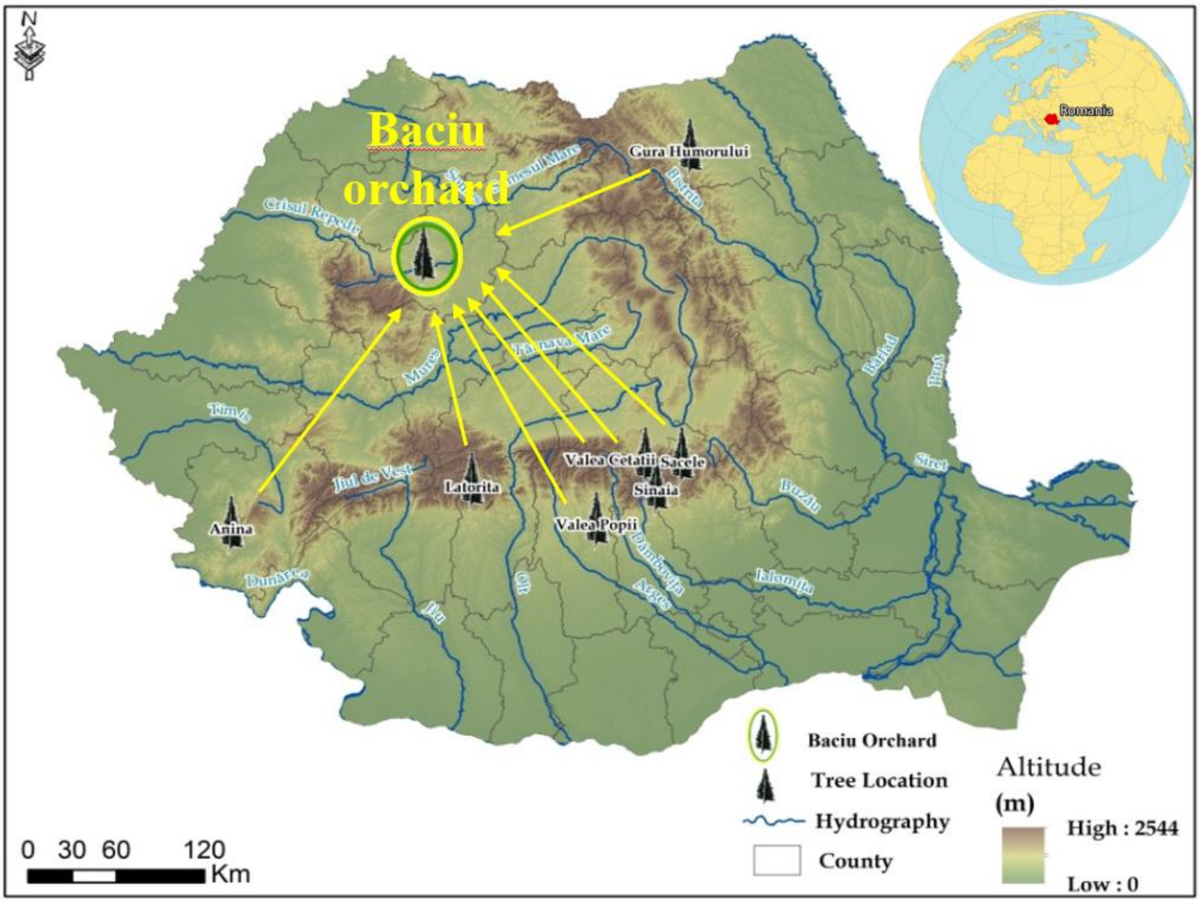

Figure 1. Location of *L. decidua* origin provenances and Baciu orchard

Characterization of Larix decidua Mill. cones and seeds

The main morphometric traits of cones and seeds including cone weight (g), cone length and width (cm), number of seeds/cones and individual seed weight (mg), as well as seed length and width (mm) were thoroughly measured and subsequently correlated with the germination capacity (%). All analyses were conducted in accordance with international ISTA standards and FAO guidelines for the assessment of forest reproductive material quality, and are given as means for each trait/provenance.

Seed germination assessment

Effect of electric fields treatments on seed germination

The influence of electric fields (EF) on seed germination was investigated at the Biophysical Laboratory of the University of Agricultural Sciences and Veterinary Medicine, Cluj-Napoca, Romania. An EF generator consisting of two electrodes with adjustable spacing, powered by a variable voltage source, was used to expose seed lots. The field intensity was controlled by modifying the distance between the electrodes and the applied voltage. In this experiment, the electrodes were 26 cm diameter and spaced 7.3 cm apart (Figure 2a). Three voltage levels (10 V, 30 V and 50 V) and three exposure durations (15, 35 and 60 minutes) were tested, along with an untreated control.

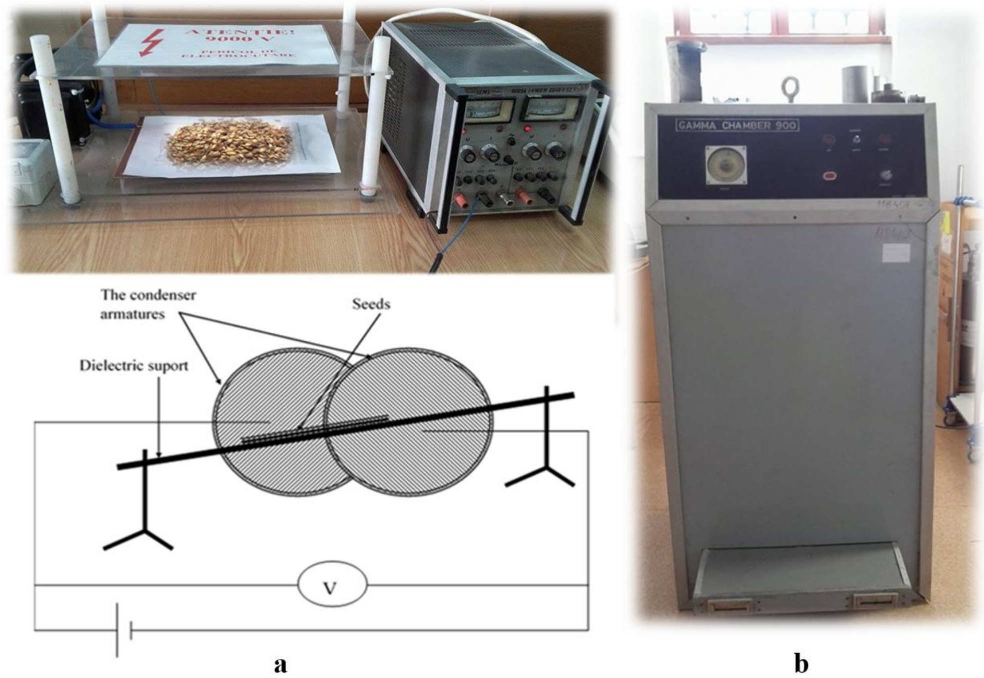

Figure 2. Exposure of larch seeds: (**a**) electric field; (**b**) γ-ray

Effect of γ-ray treatments on seed germination

The irradiation of the biological material was conducted at the Atomic and Nuclear Physics Department of Babeş-Bolyai University, Cluj-Napoca. A Gamma Chamber 900 device, using ^60 Co as the radiation source, was employed for this study (Figure 2b). The device contains a ring-shaped source with an activity of 900 Curie. Based on literature reports, the following treatments were applied: 1 Gy, 1.5 Gy, 2 Gy and 4 Gy, along with an untreated control. Germination capacity was evaluated based on germination capacity, expressed as the final germination percentage recorded after 30 days. The results provided insights into the role and effectiveness of stimulatory treatments in enhancing the germination rate and assessing the physiological quality of seeds.

Germination parameters of seeds exposed to gamma ray treatments

Seeds' germination was analyzed based on the main indices (Georgiu *et al*., 2025):

- GP (Germination percentage - %) (Fetouh and Hassan, 2014):

$$GP = \frac{Number\ of\ seeds\ germinated\ per\ day}{Total\ number\ of\ seeds\ placed\ to\ germination} \times 100$$

- Global method GI (Germination index) (AOSA, 1983):

$$GI = \frac{Number\ of\ germinated\ seeds}{Days\ from\ the\ first\ control} + \cdots + \frac{Number\ of\ germinated\ seeds}{Days\ from\ the\ last\ control}$$

- SE (Germination speed/Germinative energy) (Islam *et al*., 2009):

$$SE = \frac{Number\ of\ germinated\ seeds\ in\ the\ first\ day\ of\ germination}{Number\ of\ germinated\ seeds\ in\ the\ last\ day\ of\ germination} \times 100$$

- CRG (Coefficient of germination speed) (Bewley and Black, 1985; Chiapusio *et al*., 1997):

$$CRG = \frac{n_1 + n_2 + \cdots + n_n}{n_1 \times T_1 + n_2 \times T_2 + n_3 \times T_3 + \cdots + n_n \times T_n} \times 100$$

- n_1 = number of seeds germinated in day 1 (T1)
- n_2 = number of seeds germinated in day 2 (T2)
- n_n= number of seeds germinated in day n (Tn)

Statistical design and data analysis

The registered data for the seeds were processed as the mean of traits and standard error of the means (SEM). The graphical representation of the relationships between seed traits and germination parameters was based on descriptive and multivariate statistical analyses. ANOVA single factor was considered for data regarding the main traits of seeds and cones. If statistically significant values between averages were registered, the significance test of Tukey was applied ($\alpha = 0.05$) (Sestras, 2018). The data were subjected to a multivariate method, namely canonical correspondence analysis (CCA). A multivariate principal component analysis graph for the seven provenances of larch was created using Past software; the same software was used for the construction of a dendrogram as Euclidean distances among provenances and investigated traits.

Results

Results on the main characteristics of larch cones and seeds

The results illustrate the variation in cones' characteristics (cone weight, cone length, cone width and the number of seeds/cone) among the seven *L. decidua* provenances: Anina, Latorița, Sinaia, Gura Humorului, Brașov V.C., Săcele and Brașov V.P.

Cone length was the highest in P4 and P2 (Gura Humorului and Latorița respectively, with approximately 3.5–3.4 cm), while P5 (Brașov V.C.) presented the shortest cones (around 2.5 cm). The remaining provenances had intermediate lengths. The higher dispersion of values in Gura Humorului and Latorița provenances indicates a more heterogeneous structure of the respective populations (Figure 3a). Regarding cone width, the widest cones were recorded in P5 (Brașov V.C.) (having 2.5 cm), while P1 (Anina) had narrower cones (1.08 cm). Again, Brașov V.C. displayed greater variability, reflecting a broader range of cone morphologies (Figure 3b). Cone weight showed the highest mean values in the P2 (Latorița) and P7 (Brașov V.P.) provenances (around 4.6 g), indicating better cone development. In contrast, P1 (Anina) exhibited the lowest average cone weight (around 2.4 g), while the other provenances showed intermediate values. The higher variability observed in Latorița and Brașov V.P. populations suggests greater phenotypic diversity (Figure 3c).

The results highlight clear morphological differences among provenances, suggesting that both genetic factors and local environmental conditions influence cones' development in *L. decidua*. Provenances such as Latorița and Brașov V.P. stand out for their higher mean values and variability, while Anina showed smaller cones, potentially reflecting local adaptation or resource limitations. These variations suggest different ecological and genetic adaptations of each provenance, with significant implications for regeneration and seed production.

Results on the main characteristics of larch seeds

The results illustrate a significant variation in seed characteristics (seed weight, seed length, and seed width) among the seven *L. decidua* provenances. Regarding the seed length, the highest value was noticed in P4 (Gura Humorului), with seeds long of around 4.2 mm, indicating well developed seeds, while P6 (Săcele) showed the shortest seeds, of around 3.2 mm. Variability was more pronounced in P4 (Gura Humorului), possibly due to a wider range of environmental influences or genetic heterogeneity (Figure 4a). Seed width displayed the highest average values (around 2.4 mm), in provenance P3 (Sinaia), whereas P2 (Latorița) showed the smallest values, of 2.0 mm. The variability across provenances was relatively low, suggesting a consistent trait expression (Figure 4b). Seed weight showed the highest mean values in P3 (Sinaia), with 74.3 mg as a mean for the respective seeds, while P5 Brașov V.C. showed the lowest values, of approximately 54.2 mg. The other provenances studied displayed intermediate seed weights, between 59 and 68 mg. The relatively small variability within each provenance suggests a stable seed size pattern, except for Sinaia provenance, which showed greater dispersion (Figure 4c).

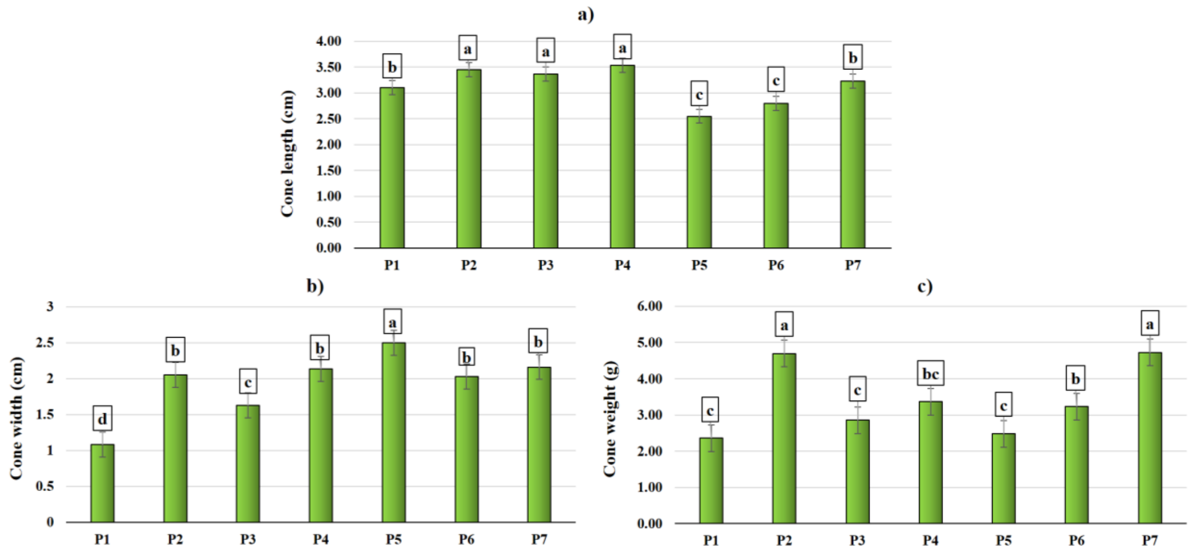

Figure 3. The principal traits of the cones, based on the provenances of *L. decidua*
The bars represent the average ± SE (n = 30). For each character, different letters from top of bars indicate significant differences between treatments, according to Tukey's test (α=0.05).
P1 (Anina), P2 (Latorița), P3 (Sinaia), P4 (Gura Humorului), P5 (Brașov V.C.), P6 (Săcele), P7 (Brașov V.P.)

The number of seeds per cone varied significantly among provenances. Provenance P2 (Latorița) fell within the highest value, having around 70 seeds/cone and indicating a higher reproductive potential, whereas P5 (Brașov V.C.) showed significantly lower number of seeds per cone. These findings underline the substantial reproductive variability among provenances and emphasize the importance of provenance selection in regeneration and seed production strategies (Figure 4d).

According to the literature, larger seeds generally exhibit higher germination rates because they contain a greater reserve of carbohydrates, lipids, and other metabolites that support the initiation of metabolic activity during germination (Kheloufi *et al.*, 2018; Tiebel and Karge, 2025). These enhanced internal resources enable seedlings to sustain early growth processes even under suboptimal environmental conditions, resulting in more vigorous and competitive individuals. Consequently, seed size is often positively correlated not only with germination capacity, but also with subsequent seedling robustness, as larger seeds tend to produce seedlings with greater biomass, improved root development, and higher survival potential in the early stages of establishment (Gorian *et al.*, 2007; Pedrol *et al.*, 2018; Holonec *et al.*, 2021). This relationship underscores the importance of considering seed mass as a key indicator of physiological quality in regeneration and breeding programs.

The hereby results indicate clear morphological differentiation among provenances. Seeds from P3, P2 and P1 (Sinaia, Latorița and Anina) appear larger and heavier, while P5 (Brașov V.C.) consistently shows smaller and lighter seeds. These differences may reflect once again both genetic variation and local environmental adaptation, influencing seed development and potential germination variation in *L. decidua* populations (Vilcan (Truta) *et al.*, 2017).

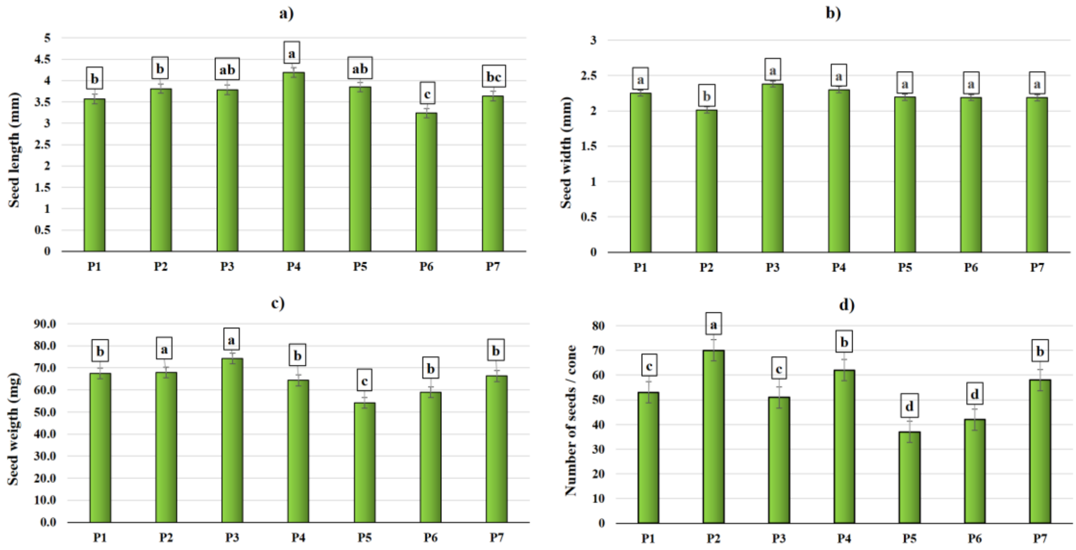

Figure 4. The principal traits of the seeds, based on the provenances of *L. decidua*

The bars represent the average ± SE (n = 30). For each character, different letters from top of bars indicate significant differences between treatments, according to Tukey's test (α=0.05).

P1 (Anina), P2 (Latorița), P3 (Sinaia), P4 (Gura Humorului), P5 (Brașov V.C.), P6 (Săcele), P7 (Brașov V.P.)

The morphological features noted in the seeds of different forest species underscore the significance of their origin (Roman *et al.*, 2022a). Similar studies have been conducted, emphasizing the relevance of understanding reproductive traits and genetic diversity across different populations (Vilcan (Truta) *et al.*, 2017; Gramazio *et al.*, 2018; Todea *et al.*, 2019; Roman *et al.*, 2022b). These studies are important as they offer valuable insights into how populations adapt to their specific environments and interact with other species within their ecosystems. Gaining knowledge about reproductive traits can guide conservation efforts, especially in the face of environmental changes and habitat degradation. Additionally, genetic diversity plays a vital role in enhancing a population's ability to withstand abiotic stress and adapt to shifting climatic conditions.

Results on germination capacity after exposing seeds in EF

The germination capacity of *L. decidua* varied significantly among provenances, electric field intensities and timing intervals (Figure 5). Among all the studied provenances (P1–P7), the highest germination percentages were recorded for P4 and P3, whereas P7 and P6 showed significantly lower germination capacities (hereafter referred to as group A), indicating a reduced physiological performance under the tested conditions.

Regarding the effect of electric field intensity, germination increased progressively with field strength. Seeds exposed to 10 V (I1) and 50 V (I3) exhibited significantly higher germination percentages (group "B") compared with the 30 V treatment (I2), which consistently remained in the lower statistical group. This pattern suggests a positive stimulatory effect of higher electric intensities on seed activation.

Similarly, the timing intervals produced significant differences. The longest exposure, T3 (60 min), resulted in higher germination values (group "C"), whereas shorter durations (T1 = 15 min and T2 = 35 min) were grouped under the lower category. These outcomes indicate that prolonged exposure enhances the physiological response to the electrical treatment. Regarding the interaction between provenance, electric field intensity and treatment duration reveals that higher voltages combined with longer exposure times substantially improve germination performance, while seeds from weaker-performing provenances remain less responsive overall (Figure 5).

Statistically significant differences were observed in the interaction between provenance and electric field intensity. This indicates that the germination response of seeds is influenced not only by the applied EF intensity, but also by the genetic origin of the seed material. The highest germination was recorded for P4I3, followed by P2I1, while the lowest was observed for P6I2. The findings indicate that some provenances are more sensitive, while others exhibit greater tolerance to variations in electric field intensity, emphasizing that the treatment's effects are influenced by the unique genetic and physiological traits of each provenance (Figure 6).

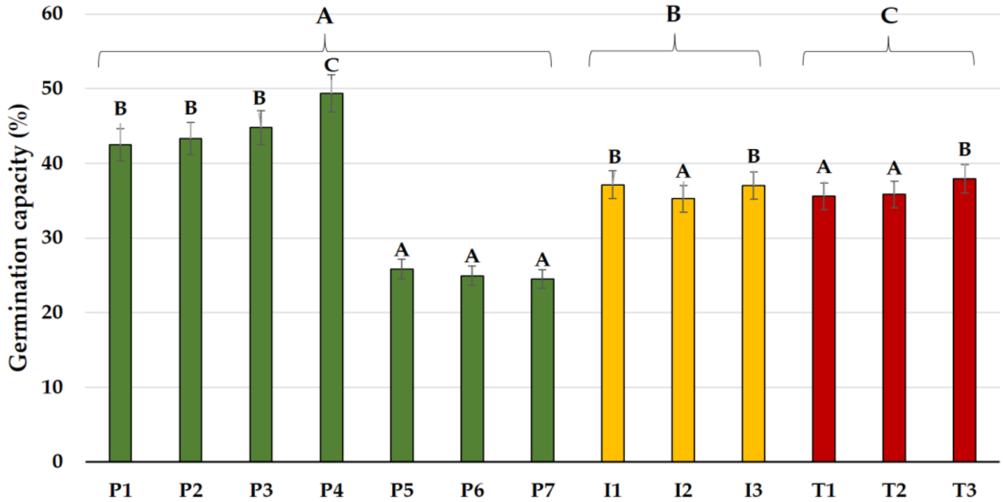

Figure 5. The effects of electric field intensity on *L. decidua* germination capacity (%) for provenance (A), intensity (B) and exposure time (C)

The bars represent the average ± SE (n = 30). For each factor, different letters from top of bars indicate significant differences between treatments, according to Tukey's test (α=0.05). P1 (Anina), P2 (Latorița), P3 (Sinaia), P4 (Gura Humorului), P5 (Brașov V.C.), P6 (Săcele), P7 (Brașov V.P.); I1 = 10V, I2 = 30V, I3 = 50V; T1 = 15 min, T2 = 35 min, T3 = 60 min.

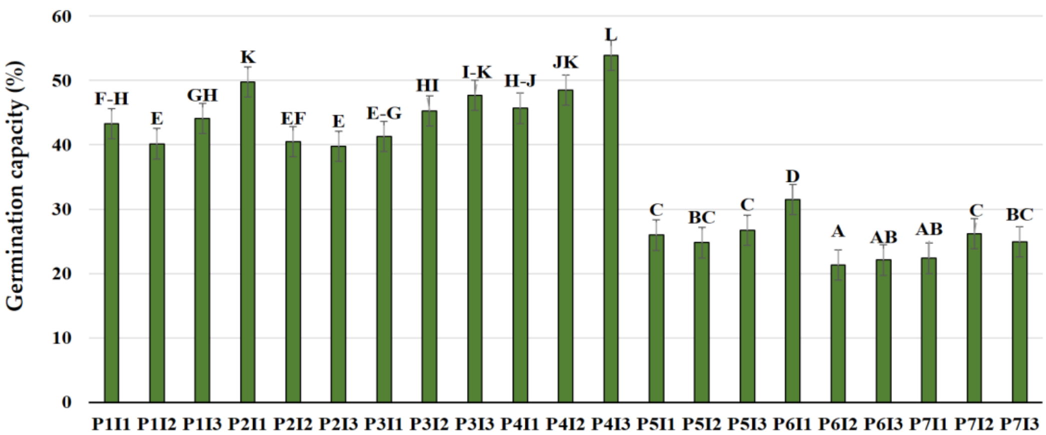

Figure 6. Germination capacity (%) of *L. decidua*, depending on the interaction between provenance and electric field intensity

The bars represent the average ± SE (n = 30). For each factor, different letters from top of bars indicate significant differences between treatments, according to Tukey's test (α=0.05). P1 (Anina), P2 (Latorița), P3 (Sinaia), P4 (Gura Humorului), P5 (Brașov V.C.), P6 (Săcele), P7 (Brașov V.P.); I1 = 10V, I2 = 30V, I3 = 50V

The interaction between provenance (P) and exposure time (T) was noted, indicating that the temporal dynamics of larch seed germination are affected by the genetic origin. This implies that various provenances demonstrate unique germination patterns over time, reflecting their intrinsic genetic and physiological characteristics that influence their response throughout the experimental period. The highest germination rates were recorded for P4T3, followed by P4T1 and P4T2, while the lowest was observed in P5T1 (Figure 7).

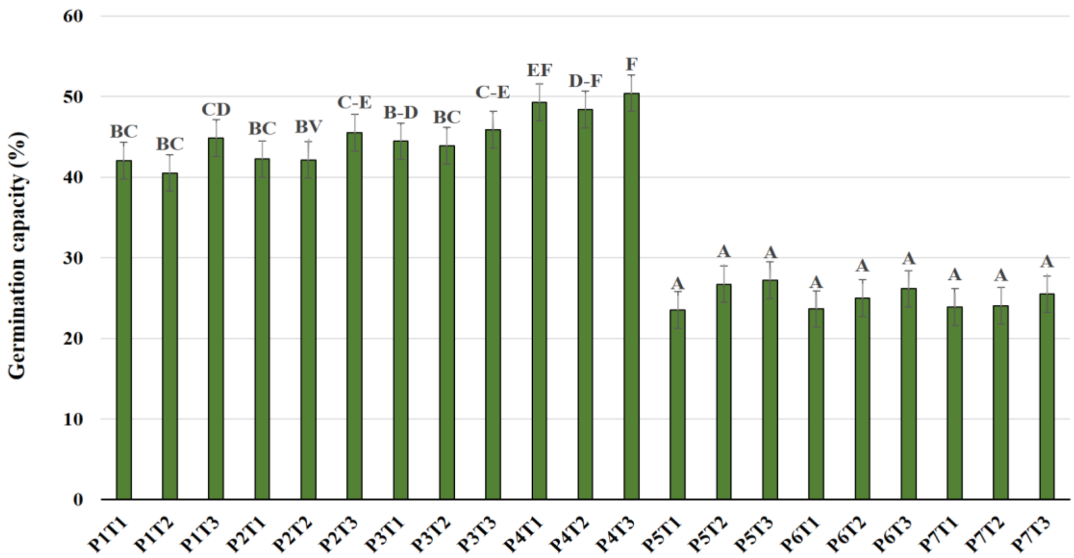

Figure 7. Germination capacity (%) on *L. decidua* depending on the interaction between provenance and EF exposure time

The bars represent the average ± SE (n = 30). For each factor, different letters from top of bars indicate significant differences between treatments, according to Tukey's test (α=0.05). P1 (Anina), P2 (Latorița), P3 (Sinaia), P4 (Gura Humorului), P5 (Brașov V.C.), P6 (Săcele), P7 (Brașov V.P.); T1 = 15 min, T2 = 35 min, T3 = 60 min.

The interaction between time (T) and electric field intensity (I) was observed, indicating that the temporal dynamics of larch seed germination are influenced by the applied treatment. This suggests that different intensities elicit distinct germination patterns over time, reflecting the inherent physiological and genetic traits of the seeds. Consequently, certain combinations of time and intensity promote higher germination rates, while others result in lower performance. The highest germination was recorded for T3I1, followed by T3I3, whereas the lowest was observed for T1I2 and T2I2, highlighting the importance of optimizing both the duration and EF intensity to maximize the germination potential of larch seeds (Figure 8).

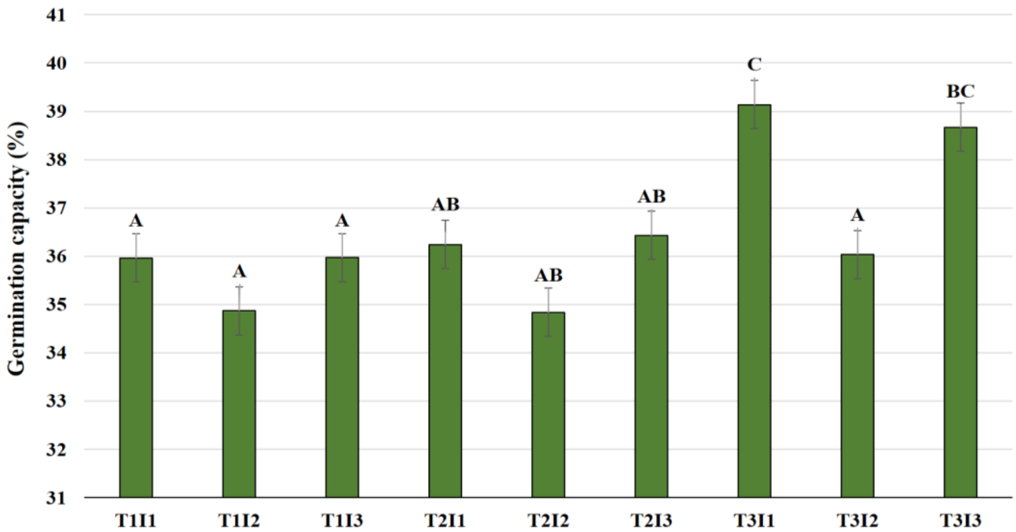

Figure 8. Germination capacity (%) on *L. decidua* depending on the interaction between exposure time and EF intensity

The bars represent the average ± SE (n = 30). For each factor, different letters from top of bars indicate significant differences between treatments, according to Tukey's test (α=0.05). T1 = 15 min, T2 = 35 min, T3 = 60 min; I1 = 10V, I2 = 30V, I3 = 50V

Results on germination capacity after exposing L. decidua seeds to γ rays

The variation within the germination indices (Table 1) highlighting the impacts of seed provenance and gamma irradiation treatments. This data illustrates how seed origin and exposure to gamma radiation can significantly affect germination rates and related metrics.

Table 1. The main germination indices depending on the provenances of *L. decidua* and the influence of the γ ray treatments on seed germination capacity (%)

No	Treatment/Provenance	Germination indices			
		GP	GI	SE	CRG
Control (no treatment)					
1	Anina	46.67	1.08	7.10	7.65
2	Latorița	40	1.04	8.30	7.84
3	Sinaia	53.33	1.21	6.30	7.39
4	Gura Humorului	40	0.93	8.30	7.80
5	Brașov V.C.	33.33	0.73	10	7.586
6	Săcele	36.67	0.88	9.1	7.33
7	Brașov V.P.	36.67	0.9	9.1	8.03
1 Gy					
1	Anina	43.33	0.94	7.7	7.93
2	Latorița	30	0.59	11.1	6.72
3	Sinaia	50	1.1	6.7	7.41
4	Gura Humorului	36.37	0.76	9.1	7.04
5	Brașov V.C.	33.3	0.71	10	7.44
6	Săcele	33.3	0.8	20	7.58
7	Brașov V.P.	36.67	0.83	9.1	7.1
1.5 Gy					
1	Anina	50	1.13	6.7	7.85
2	Latorița	36.67	0.85	9.1	7.01
3	Sinaia	60	1.35	5.6	7.33
4	Gura Humorului	43.3	1.06	7.7	7.39
5	Brașov V.C.	43.33	0.98	7.7	7.41
6	Săcele	43.33	1	7.7	7.1
7	Brașov V.P.	40	0.88	8.3	6.86
2 Gy					
1	Anina	66.67	1.64	5	7.41
2	Latorița	60	1.41	5.6	7.69
3	Sinaia	73.33	1.78	9.1	7.35
4	Gura Humorului	56.67	1.41	5.09	7.66
5	Brașov V.C.	56.67	1.38	5.9	7.39
6	Săcele	60	1.37	5.7	7.06
7	Brașov V.P.	53.33	1.24	6.3	7.17
4 Gy					
1	Anina	56.67	1.46	17.6	7.87
2	Latorița	43.33	0.99	7.7	7.1
3	Sinaia	63.33	1.59	5.3	7.66
4	Gura Humorului	46.67	1.16	7.1	7.73
5	Brașov V.C.	46.67	1.22	7.1	8
6	Săcele	46.67	1.15	7.11	7.53
7	Brașov V.P.	43.33	1.07	7.7	7.65

* GP-germination percentage, GI-germination index, SE-speed of emergence, CRG-coefficient of germination speed

Four key biological parameters were assessed: germination percentage (GP), germination index (GI), speed of emergence (SE), and coefficient of germination speed (CRG). The dataset was structured into five experimental groups: the untreated control and irradiation doses of 1 Gy, 1.5 Gy, 2 Gy and 4 Gy. Within the control group, GP values ranged from 33.33% to 53.33%, indicating inherent differences among provenances in their baseline germination capacity (Table 1).

The GI, SE, and CRG values characterize the natural germination dynamics and serve as reference points for evaluating treatment effects. Gamma irradiation induced distinct modifications depending on both the dose and the seed provenance. At 1 Gy, a slight reduction in GP and GI was observed for several provenances, suggesting an initial sensitivity to low-dose irradiation. At 1.5 Gy, the germination response became more heterogeneous, with some provenances showing increased GP and GI values, while others exhibited moderate inhibitory effects. The 2 Gy treatment produced the most pronounced stimulatory effects, reflected by increased GP and GI values across most provenances, including maximum recorded values (up to 73.33% GP for the Sinaia provenance). This dose appears to enhance both germination capacity and vigor. At 4 Gy, the response was more variable: some provenances maintaining relatively high germination indices, whereas others show declines, indicating differences in physiological tolerance thresholds (Table 1). The dataset highlights a dose-dependent and provenance-specific germination response, emphasizing the role of genetic variability in irradiation tolerance and suggesting that moderate gamma doses may act as effective stimulants for *L. decidua* seed germination. Understanding these variations is necessary for optimizing germination and enhancing the growth potential of *L. decidua* in various ecological conditions.

Canonical correspondence analysis (CCA) is a multivariate method useful for elucidating and representing the relationships between biological assemblages of species and their environment (Ter Braak and Verdonschot, 1995). In this study, seeds traits, germination treatments with γ ray and provenance of origin were analyzed and correlated in this regard. The CCA analysis reveals clear differences among the *L. decidua* provenances in their responses to γ-irradiation, outlining two main groups: Anina, Sinaia, which were predominantly associated with GP and GI treatments (including higher doses) and the group formed by Brașov V.P., Brașov V.C., Săcele and Latorița, which were more closely linked to SE and CRG treatments, while Gura Humorului exhibited an intermediate response (Figure 9).

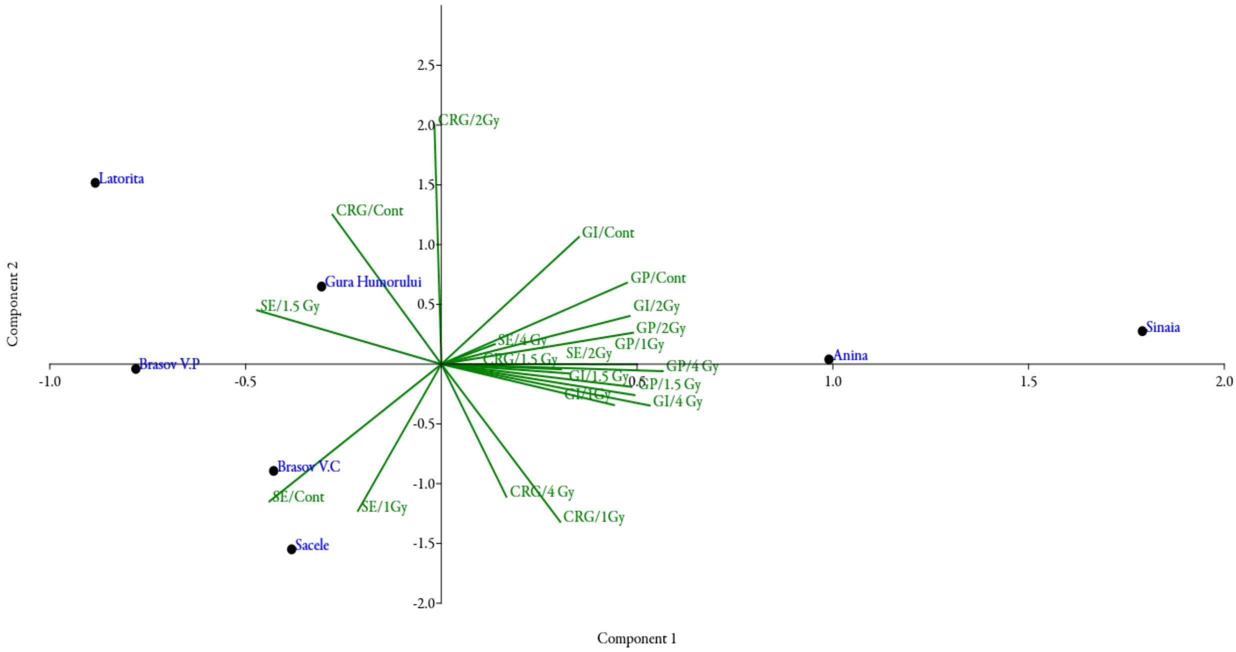

Figure 9. Canonical correspondence analysis (CCA) for the seven *L. decidua* provenances and the influence of γ ray treatments on the germination capacity

The results indicate that the intensity and type of γ-ray treatment generate distinct physiological or genetic reaction patterns among provenances, relevant for selection strategies. This suggests that γ-irradiation treatments reveal meaningful provenance-level variability that can inform future breeding and resilience programs.

The dendrogram in Figure 10 represents the clustering of treatments according to their germination response. Two major clusters can be observed (right side): one group that includes predominantly the control variants and moderate treatments, and a second group that comprises mainly the applied treatments showing similar effects induced by higher radiation doses. This pattern suggests a phenotypic convergence among some provenances regardless of treatment, while simultaneously revealing a clear separation for other provenance dose combinations. The dendrogram also reflects the similarity relationships among the seven larch provenances. Its structure indicates a functional proximity between origin such as Gura Humorului, Brașov V.C. and Brașov V.P., whereas Anina and Sinaia are distinguished by a greater distance from the other populations. This separation suggests the presence of genetic or ecological particularities influencing the germination response to irradiation. The figure illustrates how intraspecific variability and gamma-ray treatments interact to shape germination capacity in *L. decidua* and the UPGMA analysis based on the Gower similarity index provides a robust perspective on the relationships among provenances and treatments (Figure 10).

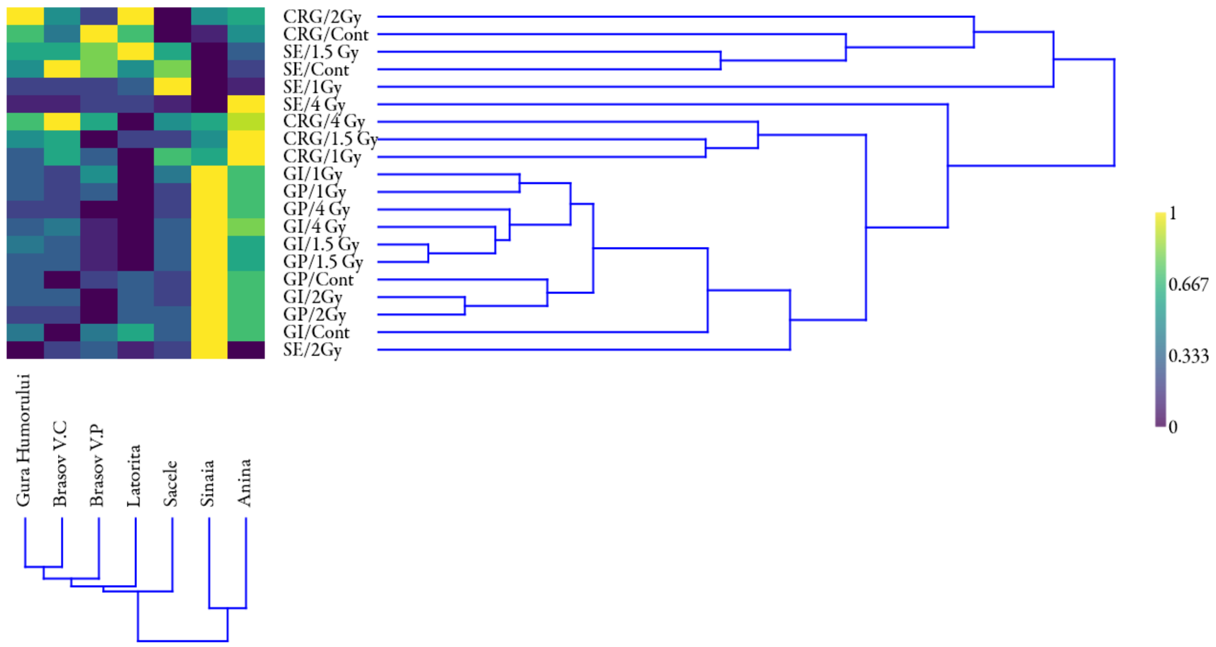

Figure 10. Hierarchical clustering-paired group UPGMA (unweighted pair group method with arithmetic mean)-similarity index (Gower) of the seven *L. decidua* provenances and the influence of the γ ray treatments on the germination capacity

The multivariate analyses employed UPGMA based on the Gower similarity index and Canonical Correspondence Analysis (CCA) consistently reveal a well-defined pattern of inter- and intra-provenance variation of *L. decidua* germination response in relation to gamma-ray treatments. The UPGMA dendrograms highlight stable groupings among certain provenances (Gura Humorului, Brașov V.C., Brașov V.P.), while others (Anina, Sinaia) exhibit distinct behavior, pointing to underlying ecological or genetic differentiation.

Discussion

The analysis of seed traits revealed pronounced differences among the seven *L. decidua* provenances. The results indicate distinct morphological divergence, suggesting that both genetic background and local environmental conditions play a central role in shaping larch cone development. Provenances such as Latorița and Brașov V.P. are characterized by higher mean trait values and greater variability, whereas Anina exhibits smaller cones, a pattern that may reflect localized adaptation processes or resource constraints. These findings highlight the existence of differentiated ecological and genetic strategies among provenances, with direct implications for natural regeneration dynamics and seed production potential. Similarly, the morphological assessment of seeds confirms clear provenance-specific differentiation. Seeds originating from P3, P2 and P1 (Sinaia, Latorița and Anina) tend to be larger and heavier, while P5 (Brașov V.C.) consistently presents smaller and lighter seeds. Such variation likely reflects the combined influence of genetic divergence and environmental selective pressures, factors that collectively shape seed development and may ultimately affect germination performance in *L. decidua* populations (Stoehr, 2000; Vilcan (Truta) *et al.*, 2017; Iralu *et al.*, 2019).

The observed morphological patterns align with previous findings in other forest species, where seed origin has been consistently identified as a critical determinant of reproductive traits (Colas *et al.*, 2008; Matsushita *et al.*, 2020; Roman *et al.*, 2022a). Comparable investigations conducted on larch and related taxa further emphasize the importance of understanding population-level variation in reproductive characteristics and genetic diversity (Schiop *et al.*, 2017; Chen *et al.*, 2018). These studies provide valuable insights into how forest populations adapt to their specific environmental contexts and interact within their ecological networks. Moreover, knowledge of reproductive traits and genetic variability is essential for guiding conservation strategies, particularly in the context of environmental change and habitat degradation (Todea *et al.*, 2019). Genetic diversity enhances population resilience by improving tolerance to abiotic stressors and facilitating adaptive responses to shifting climatic conditions.

The current findings emphasize that seed size and morphology are provenance-dependent traits influenced by both genetic factors and local environmental conditions. Such information is critical for selecting appropriate provenances for seed collection, seedling production, and forest regeneration programs, ensuring both high germination success and the maintenance of genetic diversity within *L. decidua* populations.

Regarding the germination capacity, the results of this study clearly demonstrate that the germination of larch seeds is influenced by both genetic origin (provenance) and the applied experimental treatments, namely time and electric field intensity in this case. The statistically significant interactions observed between provenance and EF intensity, provenance and exposure time, indicate that the response of larch seeds is not uniform, but rather shaped by a combination of intrinsic genetic traits and external factors. Certain provenances, such as P4, showed higher sensitivity to the applied electric field, achieving the highest germination rates under specific combinations of time and intensity (T3I1). In contrast, other provenances, such as P5 and P6, exhibited lower tolerance, reflected in reduced germination under less favorable conditions (T1I2). This variability underscores the importance of considering provenance when designing pre-sowing treatments, as genetic and physiological differences can markedly influence the effectiveness of these interventions.

The use of electric fields (EF) has been associated with several advantages, including low toxicity and minimal risk of soil or groundwater contamination (Vasilevski, 2003). Although several studies have reported positive effects of high-voltage treatments on yield and growth parameters in various species, similar approaches have increasingly been explored for forest tree species such as *Sorbus pohuashanesis* (Yang and Shen, 2011), *Picea abies* (Sîngeorzan *et al.*, 2022), *Quercus robur* (Holonec *et al.*, 2021), *Fagus sylvatica* (Česnienė *et al.*, 2023) or *Elaeis guineensis* (Sudsiri *et al.*, 2017). Similarly, Lynikeine *et al.* (2006) found that EF exposure not only increased germination rates, but also improved the overall germination performance of various horticultural taxa.

Our findings are consistent with these observations. In the present study, exposing the larch seeds to an EF for 60 minutes resulted in the highest germination increase. Shorter exposure durations of 15 and 45 minutes also produced notable improvements, enhancing germination. These results suggest that EF stimulation can act as an effective pre-sowing treatment for *L. decidua*, with longer exposure times producing stronger stimulatory effects. Moreover, the consistency between our results and previous studies reinforces the potential applicability of EF treatments in forestry practices and seed-enhancement technologies.

The CCA results reinforce this separation: most provenances cluster near the origin, indicating a relatively uniform and moderate response to varying γ-irradiation doses, whereas Anina and Sinaia are positioned at large distances along the first canonical axis, suggesting a specific sensitivity or distinct reactivity to the treatments. The irradiation vectors show subtle, structured differences among doses, but no single dominant direction, indicating a complex, provenance-dependent response.

Integrating the two analyses demonstrates that the germination response of *L. decidua* provenances is shaped by both their genetic identity and the intensity of γ-irradiation, although the provenance effect exhibits stronger structuring than the treatment effect. Notably, the provenances Anina and Sinaia consistently stand out through distinct germination behavior, suggesting that breeding strategies or tolerance-testing programs involving irradiation should account for these origin-specific differences.

From a practical silvicultural perspective, these findings highlight the necessity of tailoring pre-sowing treatments to the specific characteristics of the seed material. Optimizing both the intensity of the electric field and the duration of exposure can enhance germination success, particularly for provenances with inherently higher responsiveness. Such optimization is necessary for improving the efficiency of larch seedling production and ensuring the establishment of genetically diverse and resilient forest stands.

In conclusion, the study confirms that both genetic origin and treatment conditions interact to determine the germination outcomes of larch seeds. Future research should explore the underlying physiological mechanisms and extend these findings to field conditions, enabling the development of provenance specific protocols that maximize germination and early growth performance.

Conclusions

This research highlights the substantial influence of provenance and physical presuming treatments on the reproductive traits and germination performance of *L. decidua*. The seven provenances studied exhibited clear morphological differentiation in cones and seed characteristics, reflecting both genetic diversity and adaptation to their native environmental conditions. Germination experiments revealed that enhancement treatments based on electric fields and low-dose γ-irradiation significantly modulate germination capacity. Electric field exposure, particularly at higher intensities and longer durations, consistently improved germination, demonstrating its potential as a low-toxicity, environmentally safe stimulation method. Similarly, γ-irradiation produced a dose-dependent response, with the 2 Gy treatment yielding the most pronounced improvements in germination indices across multiple larch provenances. These effects were further supported by the multivariate analyses (CCA and UPGMA), which identified distinct physiological reaction patterns. The study demonstrates that both intrinsic genetic factors and external stimulatory treatments play essential roles in shaping germination outcomes in *L. decidua*. The observed provenance dependent responses emphasize the necessity of selecting suitable seed sources for regeneration programs, while the positive effects of EF physical treatments suggest practical opportunities for improving seedling production without relying on chemical inputs. These findings provide valuable guidance for forest managers, seed orchard specialists, and breeding programs aiming to enhance regeneration efficiency, maintain genetic diversity, and support climate-resilient management of European larch populations.

Authors' Contributions

Conceptualization: P.T., A.M.T. and L.D.; Data curation: I.M.M., C.D. and I.D.A.; Formal analysis: P.T., I.M.M., A.M.T., C.D. and O.V.; Funding acquisition: P.T., A.M.T. and O.V.; Investigation: P.T., I.M.M., A.M.T. and A.F.S.; Methodology: A.M.T., I.D.A., F.I. and A.F.S.; Project administration: P.T. and L.D.; Resources: P.T., O.V. and L.D.; Software: P.T., I.M.M., A.F.S., and L.D.; Supervision: A.F.S. and L.D.; Validation: F.I., A.F.S. and L.D.; Visualization: L.D. and F.I.; Writing - original draft: P.T., I.M.M., C.D. and A.M.T.; Writing - review and editing; F.I., A.F.S. and L.D.

Acknowledgements

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Funding

This research was conducted with partial support for P.T. from the Doctoral School of the Babeş-Bolyai University, Faculty of Physics, Cluj-Napoca, Romania.

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

References

Ahirvar BP, Chaudhry S, Kumar M, Das P (2020). Climate change impact on forest and agrobiodiversity: A special reference to Amarkantak area, Madhya Pradesh. In Contemporary Environmental Issues and Challenges in Era of Climate Change. Springer, Singapore pp 65-76.

Albert CH, Thuiller W, Lavorel S, Davies ID, Garbolino E (2008). Land-use change and subalpine tree dynamics: Colonization of *Larix decidua* in French subalpine grasslands. Journal of Applied Ecology 45(2):659-669. *https://doi.org/10.1111/j.1365-2664.2007.01416.x*

Alotaibi M (2023). Climate change, its impact on crop production, challenges, and possible solutions. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 51(1):13020-13020. *https://doi.org/10.15835/nbha51113020*

AOSA (1983). Seed vigor testing handbook. Contribution No.32 to handbook on seed testing. Association of Official Seed Analysis.

Arion ID, Arion FH, Tăut I, Mureşan IC, Ilea M, Dîrja M (2023). The efficiency of hydrotechnical works in the Gurghiu hydrographic basin. Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering 12:281-289.

Arion LD, Truta AM, Rebrean FA, Dan C, Boscaiu M, Ioras F, Morar IM (2024). Influence of geographical provenance, biostimulatory treatments and their interaction on the seed germination of *Quercus robur* L. Nova Geodesia 4(4):217. *https://doi.org/10.55779/ng44217*

Baldrian P, López-Mondéjar R, Kohout P (2023). Forest microbiome and global change. Nature Reviews Microbiology 21(8):487-501.

Bewley JD, Black M (1985). Dormancy and the control of germination. In: Seeds. Springer, Boston, MA. *https://doi.org/10.1007/978-1-4615-1747-4_5*

Blagojevic D, Lee Y, Xie L, Brede DA, Nybakken L, Lind OC, … Olsen JE (2019). No evidence of a protective or cumulative negative effect of UV-B on growth inhibition induced by gamma radiation in Scots pine (*Pinus sylvestris*) seedlings. Photochemical & Photobiological Sciences 18(8):1945-1962. *https://doi.org/10.1039/C8PP00491A*

Cairns MA, Meganck RA (1994). Carbon sequestration, biological diversity, and sustainable development: Integrated forest management. Environmental Management 18:13-22. *https://doi.org/10.1007/BF02393746*

Camarero JJ, Gazol A, Valeriano C, Vergarechea M, Cattaneo N (2024). Growth data of outlying plantations allows benchmarking the tolerance to climate extremes and drought stress in the European larch. Frontiers in Plant Science 15:1404347. *https://doi.org/10.3389/fpls.2024.1404347*

Česnienė I, Miškelytė D, Novickij V, Mildažienė V, Sirgedaitė-Šėžienė V (2023). Seed treatment with electromagnetic field induces different effects on emergence, growth and profiles of biochemical compounds in seven half-sib families of silver birch. Plants 12(17):3048. *https://doi.org/10.3390/plants12173048*

Chan Z, Yokawa K, Kim WY, Song CP (2016). ROS regulation during plant abiotic stress responses. Frontiers in Plant Science 7:1536. *https://doi.org/10.3389/fpls.2016.01536*

Chen X, Sun X, Dong L, Zhang S (2018). Mating patterns and pollen dispersal in a Japanese larch (*Larix kaempferi*) clonal seed orchard: A case study. Science China Life Sciences 61(9):1011-1023. *https://doi.org/10.1007/s11427-018-9305-7*

Chiapusio G, Sánchez AM, Reigosa MJ, González L, Pellissier F (1997). Do germination indices adequately reflect allelochemical effects on the germination process? Journal of Chemical Ecology 23:2445-2453. *https://doi.org/10.1023/B:JOEC.0000006658.27633.15*

Choi D, Makoto K, Quoreshi AM, Qu L (2009). Seed germination and seedling physiology of *Larix kaempferi* and *Pinus densiflora* in seedbeds with charcoal and elevated CO2. Landscape and Ecological Engineering 5(2):107-113. *https://doi.org/10.1007/s11355-009-0072-9*

Ciocirlan E, Sofletea N, Mihai G, Teodosiu M, Curtu AL (2021). Comparative analysis of genetic diversity in Norway spruce (*Picea abies*) clonal seed orchards and seed stands. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 49(4):12575-12575. *https://doi.org/10.15835/nbha49412575*

Colas F, Perron M, Tousignant D, Parent C, Pelletier M, Lemay P (2008). A novel approach for the operational production of hybrid larch seeds under northern climatic conditions. The Forestry Chronicle 84(1):95-104. *https://doi.org/10.5558/tfc84095-1*

Crisan V, Dinca L, Braga C, Deca S (2022). Oak reaction to future climate changes in central and eastern Romania. Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying. Environmental Engineering 11:107-114.

Curovic M, Spalevic V, Sestras P, Motta R, Dan C, Garbarino M, Vitali A, Urbinati C 2020). Structural and ecological characteristics of mixed broadleaved old-growth forest (Biogradska Gora-Montenegro). Turkish Journal of Agriculture and Forestry 44(4):428-438. *https://doi.org/10.3906/tar-2003-103*

De Micco V, Arena C, Pignalosa D, Durante M (2011). Effects of sparsely and densely ionizing radiation on plants. Radiation and Environmental Biophysics 50(1):1-19. *https://doi.org/10.1007/s00411-010-0343-8*

De Rouck B, Suls E, Duarte GT, Prinsen E, Horemans N (2025). Chronic exposure to ionizing radiation elicits growth inhibition and a dynamic oxidative stress response in the shoots of Scots pine (*Pinus sylvestris*) Seedlings. Environmental and experimental botany. Oxford, 1976, currens, 239, 1-12. *https://doi.org/10.1016/J.ENVEXPBOT.2025.106265*

Dobrowolska D, Bončina A, Klumpp R (2017). Ecology and silviculture of silver fir (*Abies alba* Mill.): A review. Journal of Forest Research 22(6):326-335. https://doi.org/10.1080/13416979.2017.1386021

El-Shakhs M, El-Naggar AAM, El-Fouly AS (2007). Response of some ornamental palm seeds to gamma irradiation. Journal of Plant Production 32(10):8373-8383. *https://doi.org/10.21608/jpp.2007.220914*

Esnault FX, Holleville D, Rossetto N, Guerandel S, Dimarcq N (2010). High-stability compact atomic clock based on isotropic laser cooling. Physical Review A-Atomic. Molecular and Optical Physics 82(3):033436. *https://doi.org/10.1103/PhysRevA.82.033436*

Farcas S, Tantau I, Turtureanu PD (2013). *Larix decidua* Mill. in Romania: Current and past distributions, kenotic preferences and conservation status. Botanical Contributions 48:39-50.

Fetouh MI, Hassan FA (2014). Seed germination criteria and seedling characteristics of *Magnolia grandiflora* L. trees after cold stratification treatments. International Journal of Current Microbiology and Applied Sciences 3(3):235-241.

Geng X, Zhang Y, Wang L, Yang X (2019). Pretreatment with high-dose gamma irradiation on seeds enhances the tolerance of sweet osmanthus seedlings to salinity stress. Forests 10(5):406. *https://doi.org/10.3390/f10050406*

Georgiu I-A, Ciulca EA, Velicevici G, Sestras RE, Boscaiu M, Vicente O, Sestras AF (2025). Eco-friendly biotechnological approaches to enhance germination efficiency in *Lavandula angustifolia* Mill. Horticulturae 1(11):1339. *https://doi.org/10.3390/horticulturae11111339*

Geras'kin S, Oudalova A, Dikareva N, Spiridonov S, Hinton T, Chernonog E, Garnier-Laplace J (2011). Effects of radioactive contamination on Scots pines in the remote period after the Chernobyl accident. Ecotoxicology 20(6):1195-1208. https://doi.org/10.1007/s10646-011-0664-7

Gorian F, Pasquini S, Daws MI (2007). Seed size and chilling affect germination of *Larix decidua* Mill. Seeds. Seed Science and Technology 35(2):508-513.

Gramazio P, Plesa IM, Truta AM, Sestras AF, Vilanova S, Plazas M, … Sestras RE (2018). Highly informative SSR genotyping reveals large genetic diversity and limited differentiation in European larch (*Larix decidua*) populations from Romania. Turkish Journal of Agriculture and Forestry 42(3):165-175. *https://doi.org/10.3906/tar-1801-41*

Hammond WM, Williams AP, Abatzoglou JT, Adams HD, Klein T, López R, Allen CD (2022). Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. Nature Communications 13(1):1761. *https://doi.org/10.1038/s41467-022-29289-2*

Hernández-Blanco M, Costanza R, Chen H, DeGroot D, Jarvis D, Kubiszewski I, Montoya J, Sangha K, Stoeckl N, Turner K, van 't Hoff V (2022). Ecosystem health, ecosystem services, and the well-being of humans and the rest of nature. Global Change Biology 28(17):5027-5040. *https://doi.org/10.1111/gcb.16281*

Holonec R, Viman O, Morar IM, Sîngeorzan S, Scheau C, Vlasin HD, … Truta AM (2021). Non-chemical treatments to improve the seeds germination and plantlets growth of sessile oak. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 49(3):12401-12401. *https://doi.org/10.15835/nbha49312401*

Iglesias-Andreu LG, Octavio-Aguilar P, Bello-Bello J (2012). Current importance and potential use of low doses of gamma radiation in forest species. Gamma Radiation 265-280.

Iralu V, Barbhuyan HSA, Upadhaya K (2019). Ecology of seed germination in threatened trees: A review. Energy, Ecology and Environment 4(4):189-210. *https://doi.org/10.1007/s40974-019-00121-w*

Islam AK, Anuar N, Yaakob Z (2009). Effect of genotypes and pre-sowing treatments on seed germination behavior of *Jatropha*. Asian Journal of Plant Science 8(6):433-439. https://doi.org/10.3923/ajps.2009.433.439

Kabir M, Habiba UE, Khan W, Shah A, Rahim S, De los Rios-Escalante PR, Shafiq M (2023). Climate change due to increasing concentration of carbon dioxide and its impacts on environment in 21st century, a mini review. Journal of King Saud University Science 35(5):102693. *https://doi.org/10.1016/j.jksus.2023.102693*

Kempf M, Hebda A, Bodziarczyk J (2023). A nature reserve as a repository of genetic richness–The case of European larch from the Gorce Mountains. Journal for Nature Conservation 74:126440. *https://doi.org/10.1016/j.jnc.2023.126440*

Kheloufi A, Mansouri L, Aziz N, Sahnoune M, Boukemiche S, Ababsa B (2018). Breaking seed coat dormancy of six tree species. Reforesta (5):4-14. *http://orcid.org/0000-0002-4928-349X*

Kiong ALP, Lai AG, Hussein S, Harun AR (2008). Physiological responses of *Orthosiphon stamineus* plantlets to gamma irradiation. American-Eurasian Journal of Sustainable Agriculture 2(2):135-149.

Kogelnig-Mayer B, Stoffel M, Schneuwly-Bollschweiler M (2013). Four-dimensional growth response of mature *Larix decidua* to stem burial under natural conditions. Trees 27(5):1217-1223. *https://doi.org/10.1007/s00468-013-0870-4*

Kondrateva NP, Krasnolutskaya MG, Dukhtanova NV, Obolensky NV (2019). Effect of ultraviolet radiation the germination rate of tree seeds. In: IOP Conference Series: Earth and Environmental Science, IOP Publishing 226(1):012049. *https://doi.org/10.1088/1755-1315/226/1/012049*

Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET, Carroll AL, Ebata T, Safranyik L (2008). Mountain pine beetle and forest carbon feedback to climate change. Nature 452(7190):987-990. https://doi.org/10.1038/nature06777

Li Y, Li X, Zhao MH, Pang ZY, Wei JT, Tigabu M, Chiang VL, Sederoff H, Sederoff R, Zhao XY (2021). An over-view of the practices and management methods for enhancing seed production in conifer plantations for commercial use. Horticulturae 7:252. *https://doi.org/10.3390/horticulturae7080252*

Liu Y, Wang C, Liu Y, Feng T, Wang E, Yang L, Niu Q, Mao X (2024). Integrating forest ecosystem services into health strategies to improve human well-being. Forests 15(11):1872. *https://doi.org/10.3390/f15111872*

Lynikiene S, Pozeliene A, Rutkauskas G (2006). Influence of corona discharge field on seed viability and dynamics of germination. International Agrophysics 20(3):195-200.

Matsushita M, Nishikawa H, Tamura A, Takahashi M (2020). Effects of light intensity and girdling treatments on the production of female cones in Japanese larch (*Larix kaempferi* (Lamb.) Carr.): Implications for the management of seed orchards. Forests 11(10):1110. *https://doi.org/10.3390/f11101110*

Mihai G, Alexandru A, Mirancea I (2019). Genetic variation and early selection in *Larix decidua* Mill. from progeny test in Romania. Annals of Forest Science 76(3):81. *https://doi.org/10.1007/s13595-019-0864-5*

Mihai G, Alexandru AM, Nita IA, Birsan MV (2022). Climate change in the provenance regions of Romania over the last 70 years: Implications for forest management. Forests 13:1203. *https://doi.org/10.3390/f13081203*

Mihai G, Teodosiu M (2018). Genetic diversity and breeding of larch (*Larix decidua* Mill.) in Romania. Annals of Forest Research 62:97-108. *https://doi.org/10.15287/afr.2009.126*

Milad M, Schaich H, Bürgi M, Konold W (2011). Climate change and nature conservation in Central European forests: A review of consequences, concepts and challenges. Forest Ecology and Management 261(4):829-843. *https://doi.org/10.1016/j.foreco.2010.10.038*

Morar IM, Dan C, Sestras RE, Stoian-Dod RL, Truta AM, Sestras AF, Sestras P (2023). Evaluation of different geographic provenances of silver fir (*Abies alba*) as seed sources, based on seed traits and germination. Forests 14(11):2186. *https://doi.org/10.3390/f14112186*

Pàques LE, Foová E, Hienze B, Lelu-Walter MA, Liesebach M, Phillipe G (2013). Larches (*Larix* sp.). In: Pàques LE (Ed). Forest Tree Breeding in Europe: Current State-of-the-art and Perspectives. Managing Forest Ecosystems. Series 25, Springer: Dordrecht, The Netherlands pp 13-123.

Pauzaite G, Malakauskiene A, Nauciene Z, Zukiene R, Filatova I, Lyushkevich V, ... Mildaziene V (2018). Changes in Norway spruce germination and growth induced by pre-sowing seed treatment with cold plasma and electromagnetic field: Short-term versus long-term effects. Plasma processes and polymers, 15(2):1700068. *https://doi.org/10.1002/ppap.201700068*

Pedrol N, Puig CG, López-Nogueira A, Pardo-Muras M, González L, Souza-Alonso P (2018). Optimal and synchronized germination of *Robinia pseudoacacia*, *Acacia dealbata* and other woody Fabaceae using a handheld rotary tool: Concomitant reduction of physical and physiological seed dormancy. Journal of Forestry Research 29(2):283-290. *https://doi.org/10.1007/s11676-017-0445-0*

Piri I, Babayan M, Tavassoli A, Javaheri M (2011). The use of gamma irradiation in agriculture. African Journal of Microbiology Research 5(32):5806-5811. *https://doi.org/10.5897/AJMR11.949*

Plesa IM, Al Hassan M, González-Orenga S, Sestras AF, Vicente O, Prohens J, Sestras RE (2019). Responses to drought in seedlings of European larch (*Larix decidua* Mill.) from several Carpathian provenances. Forests 10(6):511. *https://doi.org/10.3390/f10060511*

Roman AM, Truta AM, Morar IM, Viman O, Dan C, Sestras AF, Holonec L, Boscaiu M, Sestras RE (2022b). From seed to seedling: Influence of seed geographic provenance and germination treatments on reproductive material represented by seedlings of *Robinia pseudoacacia*. Sustainability 14:5654. *https://doi.org/10.3390/su14095654*

Roman AM, Truta AM, Viman O, Morar IM, Spalevic V, Dan C, Sestras AF (2022a). Seed germination and seedling growth of *Robinia pseudoacacia* depending on the origin of different geographic provenances. Diversity 14(1):34. *https://doi.org/10.3390/d14010034*

Roshani, Sajjad H, Kumar P, Masroor M, Rahaman MH, Rehman S, Ahmed R, Sahana M (2022). Forest vulnerability to climate change: A review for future research framework. Forests 13(6):917. *https://doi.org/10.3390/f13060917*

Schiop ST, Al Hassan M, Sestras AF, Boscaiu M, Sestras R, Vicente O (2017). Biochemical responses to drought, at the seedling stage, of several Romanian Carpathian populations of Norway spruce (*Picea abies* L. Karst). Trees 31(5):1479-1490. *https://doi.org/10.1007/s00468-017-1563-1*

Sestras AF (2018). Biostatistica si Tehnica Experimentala Forestiera: Manual Didactic. Editura AcademicPress, Cluj-Napoca, Romania.

Sestras P, Bondrea MV, Cetean H, Sălăgean T, Bilaşco Ş, Naş S, Spalevic V, Fountas S, Cîmpeanu SM (2018). Ameliorative, ecological and landscape roles of Făget Forest, Cluj-Napoca, Romania, and possibilities of avoiding risks based on GIS landslide susceptibility map. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 46(1):292-300. *https://doi.org/10.15835/nbha46110866*

Sheppard SC, Guthrie JE, Thibault DH (1992). Germination of seeds from an irradiated forest: Implications for waste disposal. Ecotoxicology and environmental safety 23(3)320-327. *https://doi.org/10.1016/0147-6513(92)90081*

Sîngeorzan SM, Holonec L, Truta AM, Morar IM, Dan C, Colişar A, ... Păcurar I (2022). The influence of physical treatments on seed germination and seedling development of spruce (*Picea abies* [L.] Karst.). Forests 13(9):1498. *https://doi.org/10.3390/f13091498*

Stoehr MU (2000). Seed production of western larch in seed-tree systems in the southern interior of British Columbia. Forest Ecology and Management 130(1-3):7-15. *https://doi.org/10.1016/S0378-1127(99)00173-5*

Sudsiri CJ, Jumpa N, Kongchana P, Ritchie RJ (2017). Stimulation of oil palm (*Elaeis guineensis*) seed germination by exposure to electromagnetic fields. Scientia Horticulturae 220:66-77. *https://doi.org/10.1016/j.scienta.2017.03.036*

Teodosiu M, Mihai G, Ciocîrlan E, Curtu AL (2023). Genetic characterization and core collection construction of European larch (*Larix decidua* Mill.) from seed orchards in Romania. Forests 14(8):1575. *https://doi.org/10.3390/f14081575*

Ter Braak CJ, Verdonschot PF (1995). Canonical correspondence analysis and related multivariate methods in aquatic ecology. Aquatic sciences 57(3):255-289. *https://doi.org/10.1007/BF00877430*

Thompson I, Mackey B, McNulty S, Mosseler A (2009). Forest resilience, biodiversity, and climate change: A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems. Secretariat of the Convention on Biological Diversity, Montreal. Technical Series 43:1-67.

Tiebel K, Karge A (2025). Influence of drought stress on the seed germination and seedling survival of *Pinus sylvestris* and *Larix decidua*. Forest Ecology and Management 591:122852. *https://doi.org/10.1016/j.foreco.2025.122852*

Todea IM, González-Orenga S, Boscaiu M, Plazas M, Sestras AF, Prohens J, ... Sestras RE (2020). Responses to water deficit and salt stress in silver fir (*Abies alba* Mill.) seedlings. Forests 11(4):395. *https://doi.org/10.3390/f11040395*

Todea IM, Gonzalez-Orenga S, Plazas M, Sestras AF, Prohens J, Vicente O, ... Boscaiu M (2019). Screening for salt and water stress tolerance in fir (*Abies alba*) populations. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 47(4):1063-1072. *https://doi.org/10.15835/nbha47411348*

Vasilevski G (2003). Perspectives of the application of biophysical methods in sustainable agriculture. Bulgarian Journal of Plant Physiology 29(3):179-186.

Vilcan (Truta) A, Mihalte (Crisan) L, Sestras AF, Holonec L, Sestras RE (2017). Genetic variation and potential genetic resources of several Romanian larch populations. Turkish Journal of Agriculture and Forestry 41(1):82-91. *https://doi.org/10.3906/tar-1610-57*

Vilcan A, Tăut I, Holonec L, Mihalte L, Sestras RE (2013). The variability of different larch clone provenances on the response to the attack by its main pests and fungal diseases. Trees 27:697-705. *https://doi.org/10.1007/s00468-012-0825-1*

Villegas D, Sepúlveda C, Ly D (2023). Use of low-dose gamma radiation to promote the germination and early development in seeds. In: Seed Biology-New Advances. IntechOpen. *https://doi.org/10.5772/intechopen.1003137*

Wagner S, Liepelt S, Gerber S, Petit RJ (2015). Within-range translocations and their consequences in European larch. PLoS ONE 10(5):e0127516 *https://doi.org/10.1371/journal.pone.0127516*

Wi SJ, Kim WT, Park KY (2006). Overexpression of carnation S-adenosylmethionine decarboxylase gene generates a broad-spectrum tolerance to abiotic stresses in transgenic tobacco plants. Plant Cell Reports 25(10):1111-1121. *https://doi.org/10.1007/s00299-006-0160-3*

World Organisation of Health and Nutrition in Agriculture (1988). Organisation of United Nations.

Wu J, Wang J, Hui W, Zhao F, Wang P, Su C, Gong W (2022). Physiology of plant responses to water stress and related genes: A review. Forests 13(2):324. *https://doi.org/10.3390/f13020324*

Yang L, Shen HL (2011). Effect of electrostatic field on seed germination and seedling growth of *Sorbus pohuashanesis*. Journal of Forestry Research 22(1):27-34. *https://doi.org/10.1007/s11676-011-0120-9*

Yudaev I, Ivushkin D, Feklistov A, Volobuev S, Petrukhin V, Prokofiev P, Panchenko V (2023). Evaluation of the Influence of Electrophysical Processing on the Germination Energy and Laboratory Germination of Seeds of Tree

Species. In: Vasant P *et al.* Intelligent Computing and Optimization. ICO 2023. Lecture Notes in Networks and Systems 1168:131-138. Springer, Cham. *https://doi.org/10.1007/978-3-031-73321-5_14*

Zhou SX, Prentice IC, Medlyn BE (2019). Bridging drought experiment and modeling: Representing the differential sensitivities of leaf gas exchange to drought. Frontiers in Plant Science 9:1965. *https://doi.org/10.3389/fpls.2018.01965*