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Laboratory seed germination of *Hydrangea* L. species depending on germination methods and genotype

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Abstract. The aim of the study was to determine the effect of germination methods and cultivar characteristics of plants of the genus *Hydrangea* L. on laboratory seed germination and to identify approaches for optimising germination protocols to obtain high-quality seeds. It was found that, on average across *Hydrangea* species, the highest seed germination (80%) was achieved on moistened filter paper, whereas the lowest germination (52%) was recorded using a paper substrate (two layers below and one above the seeds). Among all species, *Hydrangea paniculata* exhibited the lowest germination, ranging from 46% to 67% across the germination methods evaluated. The highest germination (87%) was recorded for *Hydrangea macrophylla* on moistened filter paper. Analysis of variance (ANOVA) showed that the factor 'hydrangea species' had the greatest effect on seed germination, accounting for 98.08% of the total variation. In both cultivars of *Hydrangea paniculata*, seed germination was significantly lower throughout the study than in the cultivars of *Hydrangea macrophylla* and *Hydrangea arborescens*, ranging from 64% to 68%. The results further showed that hydrangea seeds responded only slightly to pre-germination cooling. On average across species, the mean germination of non-cooled seeds was 80%. Cooling for 5 days reduced germination, whereas cooling for 10 and 20 days increased germination by only 1% relative to the non-cooled control. Irrespective of the treatment applied, the highest and nearly identical germination was observed in *Hydrangea macrophylla* and *Hydrangea arborescens*, whereas *Hydrangea paniculata* showed significantly lower germination.

Key words: variety, seed quality, germination, influencing factor, temperature.

INTRODUCTION

The genus *Hydrangea* L. belongs to the family Hydrangeaceae (Granados Mendoza et al., 2021; Yang et al., 2023). The genus *Hydrangea* comprises more than 80 species that differ in morphological characteristics and growth conditions (Yang et al., 2024). Long-term breeding efforts have resulted in the development of approximately 1,000 Hydrangea cultivars, the majority of which have been developed from *H. macrophylla* and *H. serrata*. In recent years, increasing interest in ornamental horticulture has also enhanced the popularity of other species, including *H. arborescens*, *H. paniculata* and *H. quercifolia* (Reed, 2004; Bak & Han, 2024).

Several propagation methods are used to produce new *Hydrangea* plants. In particular, hydrangeas can be propagated by seeds, cuttings, division, layering, seedlings, and micropropagation (Maharana et al., 2025; Venturieri et al., 2017). Seed propagation is one of the methods used for *Hydrangea* propagation. Hydrangea seeds are small and, under natural conditions, may remain dormant for several years until favorable conditions for germination arise. Such dormancy contributes to plant survival and species preservation (Bailey & Weiler, 1984; Nesi et al., 2023).

According to Cho et al. (2014), hydrangea seeds germinate best at 25 °C under light conditions. Seed germination capacity is influenced by the genetic characteristics established during cultivar and hybrid development, as well as by seed production conditions and pre-sowing seed treatment. At the same time, the rate and success of seed germination vary among plant species and are affected by numerous factors.

Analysis of recent research and publications. Laboratory seed germination can be assessed using various methods depending on the biological characteristics of the species. One of the major barriers to seed germination is a hard or water-impermeable seed coat, which restricts oxygen diffusion to the embryo and may consequently reduce germination (Duclos et al., 2013). Seed germination may also be affected by inhibitors (Li et al., 2010), immature embryos or their reduced physiological activity (Adkins et al., 2002), and the requirement for exposure to low temperatures (Kovalenko et al., 2024). Many researchers consider seed dormancy in most species to be regulated by the hormonal system, particularly by the presence of indoleacetic acid (Li et al., 2010) and abscisic acid (Finch-Savage & Leubner-Metzger, 2006; Dryha et al., 2022), as well as by the concentration of gibberellins (Kurilo et al., 2019).

Laboratory germination tests for most crop species are conducted by germinating seeds at 20–25 °C in a germination chamber for a specified period either on moistened paper or between two layers of moistened paper. When freshly harvested seeds have not completed physiological after-ripening, various dormancy-breaking treatments are applied, including pre-cooling, warming, washing, or treatment of the germination substrate with chemical substances (Doronin et al., 2019). For example, when studying seeds characterized by a high level of biological dormancy, such as switchgrass (*Panicum virgatum* L.), germination is determined at 20 °C between two strips of moistened paper after pre-cooling at 10 °C for 7 days (Doronin et al., 2021). Sugar beet seeds are germinated at 20 °C on moistened corrugated filter paper after washing to remove growth inhibitors from the seeds (except for pelleted seeds, which are not washed).

Seeds carry the biological and economically valuable traits of plants, which substantially determine the yield and quality of the harvested material. Therefore, seed quality control is an essential practice, the implementation of which is impossible without the use of established methods for assessing seed sowing qualities (Demianiuk et al., 2022). One of the main indicators of seed quality is germination. This parameter is of particular importance in seed trade and cultivar propagation (Demianiuk et al., 2021).

Studies by Oleksiak et al. (2023) have shown that seed quality depends on germination conditions and genotype. In particular, during the germination of perennial ryegrass (*Lolium perenne* L.) seeds, germination percentage of all samples on sand was on average 44% lower than on filter paper. Genotype also affected seed germination, with variation among varieties reaching about 10%. Studies on *Silybum marianum* seed

germination showed that germination in rolls of filter paper was more suitable than germination on sand (Rosinka et al., 2018).

Cold treatment is a common method for breaking physiological dormancy in tree seeds and promoting germination; however, its effectiveness depends on the temperature and duration of exposure. Greer & Rinehart (2009) found that dry storage of *H. macrophylla* and *H. paniculata* seeds at 4 °C for six weeks increased their germination rates. At the same time, under conditions of climate warming, rising winter temperatures may affect the breaking of seed dormancy. Song et al. (2023) noted that investigating the effects of elevated cold-stratification temperatures, particularly up to 10 °C, is important for predicting the potential responses of populations to future climate change. Wang et al. (2009) established that the release of *V. vinifera* × *V. amurensis* seeds from dormancy depended on both temperature and the duration of stratification, with the greatest increase in germination observed at 10 °C. Kirdar & Ertekin (2008) also demonstrated that cold stratification at 9 °C was more effective than at 4 °C in breaking dormancy in *Abies nordmanniana* seeds. Furthermore, Rawat et al. (2008) reported the highest germination rate at 10 °C. Thus, these findings support the rationale for investigating 10 °C as an elevated cold-treatment regime in the context of climate warming.

Despite the availability of well-established laboratory protocols for evaluating seed germination in numerous plant species, information on suitable laboratory methods for assessing the germination of *Hydrangea* seeds remains very limited.

The aim of the study was to determine the effects of germination methods and plant genotype within the genus *Hydrangea* L. on laboratory seed germination and to identify effective germination methods for obtaining high-quality seed material. To achieve this objective, the laboratory germination rates of seeds from different species and cultivars of the genus *Hydrangea* L. were determined depending on the germination method and genotype, and the effect of pre-cooling the seeds on their germination rate was also assessed.

MATERIALS AND METHODS

Laboratory studies of hydrangea genotypes (species and cultivars) were conducted in 2020–2024 at Uman National University of the Ministry of Education and Science of Ukraine and at the National Dendrological Park ‘Sofiyivka’ of the National Academy of Sciences of Ukraine.

Research conditions

Prior to being placed on filter paper in Petri dishes, the hydrangea seeds were rinsed five times with distilled water. To determine germination rates under different germination methods, the seeds were germinated on moistened paper (two layers below and one layer above the seeds), on paper (two layers below the seeds), and in corrugated paper at a constant temperature of 20 °C in a thermostatically controlled chamber under a 16-hour photoperiod with a light intensity of 3 klx. The moisture content of the paper was maintained by spraying it with water when necessary.

To determine the effect of cold treatment on seed germination, one cultivar of each of three hydrangea species was studied: *H. macrophylla* ‘Forever and Ever’,

H. paniculata ‘Diamant Rouge’ and *H. arborescens* ‘Arborescens’. Prior to germination, the seeds were subjected to cold treatment on moistened filter paper at 10 °C for 5, 10, or 20 days. After cold treatment, the seeds were germinated at a constant temperature of 20 °C in a thermostatically controlled chamber under illumination. The control treatment consisted of seeds germinated without prior cold treatment under the same conditions.

Three replicates of 50 seeds each were used for the experiment. Laboratory germination was assessed on the 15th day after the onset of germination in each replicate.

Plant material

The study of methods for assessing laboratory seed germination under different germination conditions and in relation to cultivar characteristics was conducted using hydrangea species and cultivars: *Hydrangea macrophylla* ‘Nikko Blue’ and ‘Forever and Ever’, *Hydrangea paniculata* ‘Grandiflora’ and ‘Diamant Rouge’, *Hydrangea arborescens* ‘Annabelle’ and ‘Arborescens’.

Seeds were collected from well-developed, healthy plants free from diseases and pest damage during dry weather at the end of the growing season (late November to early December). All mature inflorescences were collected and subsequently dried in a dry, well-ventilated room. After drying, the seeds were separated from the inflorescence residues by mechanical cleaning, followed by removal of impurities. Until germination, the seeds were stored in tightly sealed paper bags in a dry, cool, dark, and well-ventilated room at +10 to +15 °C and a relative humidity not exceeding 50%. Fully mature seeds that were dark brown or brownish-black in colour and free from mechanical damage, visible signs of disease, or frost damage were used for the study.

Statistical analysis

Statistical methods, including correlation and regression analysis, as well as methods of analysis and synthesis, were used to process the research results. Statistical data were analysed using analysis of variance (ANOVA), correlation, and regression analyses according to Fisher (2006) and methodological recommendations of (Ermantraut et al. (2007). A two-way analysis of variance (ANOVA) was performed for each experiment to assess the effects of the two main factors under study, their interaction, and residual variation. In the experiment investigating the effect of germination method, the factors ‘hydrangea species’ and ‘germination method’, their interaction (‘hydrangea species × germination method’), and residual variance attributable to other factors not included in the model were considered. To assess cultivar-specific differences, the factors ‘species’ and ‘cultivar’, their interaction (‘species × cultivar’), and residual variance were analysed. In the experiment investigating the effect of pre-sowing cold treatment, the factors ‘hydrangea species’ and ‘cold treatment’, their interaction (‘hydrangea species × cold treatment’), and residual variance were evaluated.

For multiple comparisons of means following analysis of variance, Fisher’s least significant difference (*LSD*) test was used at a significance level of $P \leq 0.05$. Statistically significant differences between means are indicated by different letters, whereas means followed by the same letters do not differ significantly.

RESULTS AND DISCUSSION

Adverse environmental conditions-including high temperatures, soil salinity, lack of available water, low soil water-holding capacity, and poor soil fertility-have a negative impact on seed germination and seedling emergence. Under such conditions, an important task is to find effective ways to improve seed germination and ensure uniform and consistent germination (Jarrar et al., 2023).

Germinating seeds on filter paper is a widely accepted method for evaluating seed sowing quality, as it provides standardised conditions for moisture, aeration, and seed contact with a moistened medium, minimising the influence of the substrate on the results. Therefore, the germination rates obtained reflect the biological potential of seeds from different *Hydrangea* cultivars and can serve as a baseline for developing seed germination technologies.

The results of the study showed that, on average across hydrangea species, significantly higher seed germination was obtained when seeds were germinated on moistened filter paper (80%), whereas significantly lower germination (52%) was recorded on a paper substrate consisting of two layers below the seeds and one layer above (Fig. 1).

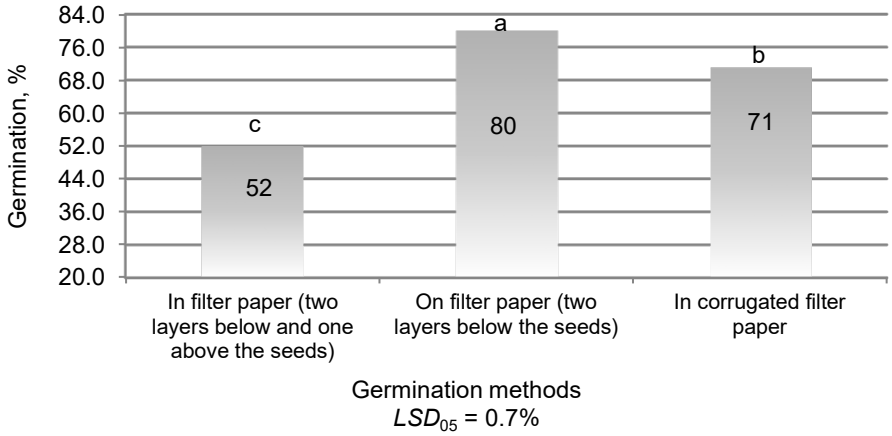


Figure 1. Laboratory seed germination rates depending on germination methods (average for 2021–2024).

Different letters indicate statistically significant differences between germination method ($P < 0.05$).

Similar results were obtained depending on the species-specific characteristics of hydrangea. Significantly higher germination was recorded when seeds were germinated on filter paper, whereas substantially lower germination was observed when seeds were germinated between paper layers in all hydrangea species (Table 1). *Hydrangea paniculata* showed the lowest germination under all germination methods. In *Hydrangea macrophylla* and *Hydrangea arborescens*, the highest germination was recorded on filter paper, reaching 87% and 85%, respectively, with germination significantly higher in *Hydrangea arborescens*. Even when seeds were germinated between paper layers, germination in these species was significantly higher than that of *Hydrangea paniculata*, whose germination

under this treatment was only 46%. When hydrangea seeds were germinated in corrugated paper, germination of all species was significantly lower than that on filter paper but significantly higher than that between paper layers. In particular, germination of *Hydrangea macrophylla* and *Hydrangea arborescens* in corrugated paper was 21% higher than that between paper layers, but 8% and 12% lower than that on filter paper for *Hydrangea arborescens* and *Hydrangea macrophylla*, respectively.

Similar patterns of seed germination depending on germination methods and species-specific characteristics were observed across the study years.

Table 1. Seed germination depending on germination methods and *Hydrangea* species (average for 2021–2024)

Species	Cultivar	Laboratory germination, %
Germination at 20 °C between filter paper (two layers below and one above the seeds)		
Hydrangea macrophylla	Forever and Ever	54[b]
Hydrangea paniculata	Diamant Rouge	46[c]
Hydrangea arborescens	Arborescens	56[a]
Germination at 20 °C on filter paper (two layers below the seeds)		
Hydrangea macrophylla	Forever and Ever	87[b]
Hydrangea paniculata	Diamant Rouge	67[c]
Hydrangea arborescens	Arborescens	85[a]
Germination at 20 °C in corrugated filter paper		
Hydrangea macrophylla	Forever and Ever	75[b]
Hydrangea paniculata	Diamant Rouge	62[c]
Hydrangea arborescens	Arborescens	77[a]
$LSD_{05\ general}$		1.3
$LSD_{05\ germination}$		0.7
$LSD_{05\ species}$		0.7

Different superscript letters next to the germination percentages indicate statistically significant differences between hydrangea species within the same germination method ($P < 0.05$).

Analysis of variance revealed that the factor 'hydrangea species' had the greatest influence on laboratory seed germination, accounting for 99.4%. The influence of the factor 'germination method' was insignificant, accounting for 0.5%. The interaction between the factors 'hydrangea species × germination method' accounted for only 0.05% of the variability, while other factors not included in the model accounted for a further 0.05%. The resulting distribution of variance indicates a pronounced dominance of species-specific effects in determining the laboratory germination percentage of the studied hydrangea species. In other words, differences between species accounted for the vast majority of the total variability in germination, whereas the germination methods used made a comparatively minor contribution. The low proportion of variance attributable to the interaction between the factors indicates that the effect of the germination method did not differ substantially among the studied species under the conditions of the experiment.

Experimental studies showed that hydrangea seed germination should preferably be determined by germinating seeds on moistened paper (two layers below) at a constant temperature of 20 °C in a thermostatically controlled chamber with illumination. Therefore, the germination of cultivars of three hydrangea species was determined using this method.

It was found that the germination of seeds of *Hydrangea macrophylla* and *Hydrangea arborescens* cultivars was almost identical, ranging from 85 to 87%. No significant differences were detected depending on the hydrangea species or cultivar characteristics (Fig. 2).

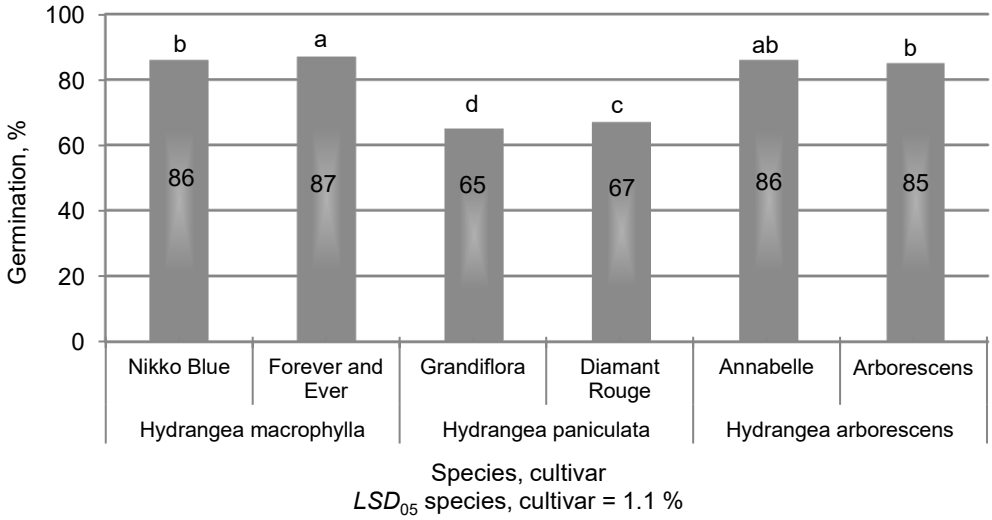


Figure 2. Laboratory seed germination rates depending on the species and cultivar of *Hydrangea* (average for 2021–2024).

Different letters indicate statistically significant differences between species and cultivars based on Fisher's *LSD* test at a significance level of $P < 0.05$.

The germination of seeds of both *Hydrangea paniculata* cultivars was significantly lower; however, it was significantly higher in the cultivar Diamant Rouge, reaching 67%.

Analysis of variance (ANOVA) revealed that the factor 'hydrangea species' had the most significant effect on seed germination accounting for 98.08%. The contribution of the 'cultivar' factor was considerably smaller, accounting for 0.42% of the variance, while the 'species × cultivar' interaction also accounted for 0.42% of the variability. Other factors not included in the model accounted for 1.08% of the total variance. Thus, differences between hydrangea species accounted for the vast majority of the variability in the studied trait, whereas the contributions of cultivar-specific effects and their interaction with species were relatively small. This indicates that, under the conditions of the experiment, species identity was the primary factor associated with differences in seed germination. The small proportion of variance attributable to cultivar and the 'species × cultivar' interaction does not imply a complete absence of their biological effects, but rather indicates their substantially smaller relative contribution compared with interspecific differences. At the same time, the proportion attributable to other factors (1.08%) indicates the presence of some residual variability, which may have resulted from unaccounted-for biological or experimental factors.

Analysis of the research results on the influence of species and cultivar characteristics on seed germination across the years of the study showed that both on

average over four years and in individual years, the highest seed germination was observed in *Hydrangea macrophylla* and *Hydrangea arborescens*, ranging from 84–88% and 84–87%, respectively (Table 2). No significant differences in seed germination depending on cultivar characteristics were detected.

Table 2. Seed germination of *Hydrangea* when germinated on paper at a constant temperature of 20 °C depending on species and cultivar characteristics over the years of research (average for 2021–2024)

Species	Cultivar	Germination, %			
		2021	2022	2023	2024
Hydrangea macrophylla	Nikko Blue	84^{b}	85^{a}	86^{a}	87^{ab}
	Forever and Ever	86^{ab}	87^{a}	87^{a}	88^{a}
Hydrangea paniculata	Grandiflora	65^{c}	65^{b}	67^{c}	64^{d}
	Diamant Rouge	66^{c}	66^{b}	68^{b}	68^{c}
Hydrangea arborescens	Annabelle	86^{ab}	86^{a}	87^{a}	86^{ab}
	Arborescens	87^{a}	85^{a}	86^{a}	84^{b}
$LSD_{05\ \text{general}}$		3.5	3.2	3.4	3.5
$LSD_{05\ \text{species, cultivar}}$		2.1	3.3	2.2	3.5

Different superscript letters within each year indicate statistically significant differences between species and cultivars based on Fisher's *LSD* test at a significance level of $P < 0.05$.

Seed germination of *Hydrangea paniculata* was significantly lower and averaged 66% over the years of the study. No significant differences in seed germination of *Hydrangea paniculata* on average over the study years were observed depending on cultivar characteristics. Thus, in 2021, seed germination of the cultivar 'Grandiflora' was 65%, while that of the cultivar 'Diamant Rouge' was 66% (LSD_{05} for species and cultivar = 2.1%). At the same time, the greatest difference in seed germination between the cultivars *Hydrangea paniculata* 'Grandiflora' and 'Diamant Rouge' was observed in 2024: germination was 64% and 68%, respectively. The difference between the cultivars was 4 percentage points, exceeding the LSD_{05} value for species and cultivar (3.5%), and was therefore statistically significant.

One of the approaches to increasing seed germination is exposure to stress conditions during the germination period, particularly low temperatures. Considering the positive results obtained in previous studies with other crops-switchgrass (Doronin et al., 2019; Dryha, 2020) and freshly harvested winter wheat seeds characterised by a high level of biological dormancy-an experiment was conducted in which the seeds were cooled on moistened filter paper at 10 °C for 5, 10, and 20 days prior to germination at 20 °C on moistened filter paper in a thermostat.

It was found that hydrangea seeds showed almost no response to cooling prior to germination (Fig. 3). Without cooling, the average seed germination of hydrangea species was 80%. Cooling for 5 days reduced germination to 76%, whereas cooling for 10 and 20 days increased germination by only 1% compared with the control (without cooling). Thus, this treatment did not result a significant increase in hydrangea seed germination.

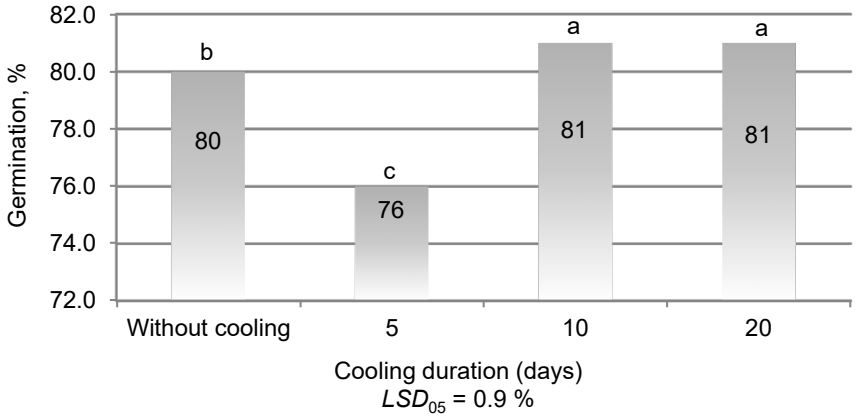


Figure 3. Germination rate of *Hydrangea* seeds depending on germination conditions and species (average for 2021–2024).

Different letters indicate statistically significant differences between cold-treatment durations at the 5% significance level, according to Fisher's *LSD* test.

A similar trend was observed for hydrangea species. When seeds of all hydrangea species and cultivars were cooled for 5 days, seed germination decreased by 2–5% compared with the control (without cooling) (Table 3). Cooling the seeds for 10 and 20 days resulted in an increase in seed germination compared both with the control (without cooling) and with the 5-day cooling treatment.

Table 3. Seed germination depending on germination conditions and hydrangea species (average for 2021–2023)

Species, Cultivar	Germination temperature	Cooling duration at 10 °C (days)	Germination, %
Hydrangea macrophylla Forever and Ever	At a constant temperature of 20 °C	without cooling	87[b]
		5	82[c]
		10	88[a]
		20	88[a]
Hydrangea paniculata Diamant Rouge	At a constant temperature of 20 °C	without cooling	67[b]
		5	64[c]
		10	68[a]
		20	68[a]
Hydrangea arborescens Arborescens	At a constant temperature of 20 °C	without cooling	85[c]
		5	83[c]
		10	87[b]
		20	88[a]
$LSD_{05\ general}$			2.2
$LSD_{05\ species}$			1.1
$LSD_{05\ cooling}$			1.3

Different superscript letters within each 'species–cultivar' combination indicate statistically significant differences between cold-treatment durations at the 5% significance level, according to Fisher's *LSD* test.

For example, after 20 days of cooling, seed germination of *Hydrangea arborescens* increased by 5% compared with the 5-day cooling treatment and by 3% compared with the control (without cooling).

No significant differences in seed germination were detected between cooling for 10 and 20 days, as the values were identical. Among hydrangea species, the highest and similar levels of seed germination were observed in *Hydrangea macrophylla* and *Hydrangea arborescens*, whereas significantly lower germination was recorded in *Hydrangea paniculata*.

Thus, similar to the average values for hydrangea species, cooling the seeds for 10 and 20 days prior to germination at a constant temperature resulted in a statistically significant increase in seed germination for each species. However, this increase was not substantial, as the germination of *Hydrangea paniculata* seeds was the lowest – 67% without cooling - and the application of this treatment increased it by only 3%.

Analysis of variance revealed that the 'hydrangea species' factor made the largest contribution to the variability in laboratory seed germination, accounting for 99.4% of the total variance. The contribution of the 'cold treatment' factor was minor, accounting for 0.5%. The interaction between 'hydrangea species' and 'cold treatment' explained only 0.03% of the total variability, while other factors not included in the model accounted for 0.07%. This distribution of variance indicates a pronounced dominance of species-specific effects in determining the laboratory germination of the studied hydrangea species. Approximately 99% of the total variability in germination was associated with interspecific differences, whereas the duration of cold treatment under the regimes used in the experiment made a considerably smaller relative contribution. At the same time, the extremely low proportion of variance attributable to the 'hydrangea species × cold treatment' interaction (0.03%) indicates that the responses of the studied species to the applied cold-treatment regimes did not differ substantially under the experimental conditions. The minor contribution of the 'cold treatment' factor should not be interpreted as indicating a complete absence of a biological effect. Rather, this value reflects its relative contribution to the overall variability in germination under the specific temperature regimes and treatment durations used in the experiment. Thus, certain differences in seed germination following cold treatment may have occurred, but their magnitude was considerably smaller than that of the interspecific differences.

Research by Wiedemann et al. (2015) revealed that seed germination and the maintenance of seedling viability are complex stages of generative propagation that pose challenges for breeding programs. Jones & Reed (2005) also reported low efficiency in obtaining viable seed progeny through *Hydrangea* hybridization.

Greer & Rinehart (2009) found that cold treatment had a positive effect on seed germination in *H. macrophylla* and *H. paniculata*. Cold treatment increased the overall germination rate over a 21-day period by 10–40%, depending on the conditions. Our results are partially consistent with these findings, as cooling the seeds at 10 °C for 5 days reduced germination, whereas 10- and 20-day treatments resulted in only a slight increase in germination compared with the control. The lack of a significant difference between the 10- and 20-day cooling treatments indicates the limited effectiveness of this method. These differences may be related to variations in the cold-treatment regimes. Greer & Rinehart (2009) used dry cold storage of seeds at 4 °C for six weeks, whereas

in our study, the seeds were cooled under moist conditions at 10 °C for 5, 10, and 20 days. Therefore, the positive effect of cold treatment cannot be considered universal across all genotypes and treatment regimes, as its effectiveness likely depends on temperature, treatment duration, seed moisture content, and physiological state.
Greer & Rinehart (2010) also found that light conditions affect seed dormancy and germination, with the nature and magnitude of this effect depending on the species and cultivar. At the same time, the response of seeds to light conditions varied depending on cultivar characteristics. In particular, most cultivars of *H. macrophylla* showed a tendency toward higher overall germination under continuous illumination, whereas this pattern was not observed in *H. paniculata*, indicating a species-specific response of seeds to the light regime. The results reported by Feng et al. (2022) also indicate low germination of *H. paniculata* seeds and a significant influence of seed preparation and storage conditions on germination. These findings are consistent with our results, according to which *H. macrophylla* and *H. arborescens* exhibited high and similar germination rates, whereas *H. paniculata* showed a significantly lower germination rate regardless of the germination method used. This indicates pronounced species-specificity in seed germination within the genus *Hydrangea* and highlights the need to consider species identity when developing protocols for its generative propagation.

The high proportion of variance attributable to the species factor (98.08–99.5%), compared with the negligible contribution of the germination method and cooling duration (0.5%), further confirms the predominance of species-specific effects in determining the germination of the seeds studied. At the same time, the negligible contribution of the technological factors examined does not imply the absence of a biological effect; rather, it indicates that, under the experimental conditions used, their effects were substantially weaker than the differences among species.

The results of this study complement existing knowledge of the physiology of *Hydrangea* seeds and demonstrate that improving the efficiency of generative propagation requires that species-specific characteristics be considered as a primary factor. Germination on moistened filter paper at 20 °C under light conditions can be recommended as a simple and effective laboratory method for assessing the germination capacity of the studied species. At the same time, the limited effectiveness of short-term cold treatment observed in this study indicates the need for further investigation of the duration, temperature, and method of stratification, as well as the potential for combining cold treatment with light-regime manipulation and the application of germination stimulants.

At the same time, establishing optimal laboratory conditions is only the first step toward developing a practical technology for seed propagation. Current research indicates that, after determining optimal germination parameters under laboratory conditions, the next step is to adapt these findings to production conditions through the selection of suitable substrates, pre-sowing hydration, seed pelleting and conditioning, biodegradable mats, and other materials capable of maintaining optimal water and air conditions around the seeds (Taylor et al., 2007; Pedrini et al., 2020). Biodegradable nanomaterials used for seed coating can enable the targeted delivery of nutrients and enhance stress tolerance while protecting beneficial soil microbiota (Durgadevi et al., 2025; Biswal et al., 2026). Modern seed encrusting, pelleting, and film-coating technologies are also considered effective tools, particularly for crops characterized by

uneven germination. In addition to improving the efficiency and precision of sowing, such materials can regulate the rate of water uptake, thereby reducing the risk of seed damage caused by rapid fluctuations in moisture content (Afzal et al., 2020). Another promising area is the development of biodegradable mats and nonwoven fabrics made from biomaterials that provide adequate aeration and water retention, which are important for successful seed germination (Devrim et al., 2024; Gowthaman et al., 2026).

Thus, a promising area for further research is the validation of the established laboratory parameters under substrate-based and production conditions using modern methods of pre-sowing seed treatment and coating, particularly biodegradable materials and biopolymers.

CONCLUSION

It was established that, on average across hydrangea species, the highest seed germination (80%) was obtained when seeds were germinated on moistened filter paper, whereas the lowest germination (52%) occurred when seeds were germinated between paper, with two layers below and one layer above the seeds. The lowest germination rate across all germination methods was recorded for *Hydrangea* paniculata (46–67%), whereas the highest was recorded for Hydrangea macrophylla (87%) when seeds were germinated on filter paper. Analysis of variance (ANOVA) showed that the factor 'hydrangea species' had the greatest influence on seed germination, accounting for 98.08% of the total variation. It was found that pre-cooling soaked hydrangea seeds at 10 °C had a negligible effect on their germination rate. Cooling the seeds for 5 days reduced germination by 4%, whereas cooling for 10 and 20 days increased germination by 1% compared with the control (without cooling). Depending on the hydrangea species, the highest and similar seed germination was observed in *Hydrangea macrophylla* and *Hydrangea arborescens*, whereas significantly lower germination was recorded in *Hydrangea paniculata*.

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