UNIVERSIDADE FEDERAL DE SÃO CARLOS
CENTRO DE CIÊNCIAS E TECNOLOGIAS PARA A SUSTENTABILIDADE
CAMPUS DE SOROCABA
PROGRAMA DE PÓS-GRADUAÇÃO EM PLANEJAMENTO E USO DE RECURSOS RENOVÁVEIS

Ana Paula Ponce Shiguehara

Respostas germinativas de sementes empregadas na semeadura direta e seus impactos frente às mudanças climáticas

Sorocaba
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Dissertação apresentada ao Programa de Pós-Graduação em Planejamento e Uso de Recursos Renováveis para obtenção da qualificação no programa.

Orientação: Prof.ª Dr.ª Fátima Piña Rodrigues

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RESUMO

SHIGUEHARA, Ana Paula Ponce. Respostas germinativas de sementes empregadas na semeadura direta e seus impactos frente às mudanças climáticas. 2024. Defesa (Mestrado em Planejamento e Uso de Recursos Renováveis) – Universidade Federal de São Carlos, Sorocaba, 2024.

As mudanças climáticas impõem desafios significativos aos ecossistemas globais, impactando particularmente a germinação de sementes em espécies florestais nativas. Este estudo investiga a resposta da germinação de 13 espécies florestais brasileiras a regimes de temperatura simulados que imitam cenários climáticos projetados. As sementes foram submetidas a cinco tratamentos de temperatura, variando de 25-50°C, e monitoradas semanalmente quanto à emergência da radícula. Para a análise dos dados, cada espécie incluiu a porcentagem de germinação (%G), o índice de velocidade de germinação (GSI) e os modelos lineares generalizados mistos (GLMM). Os resultados revelam respostas variáveis de germinação entre as espécies, com algumas exibindo taxas de germinação reduzidas em temperaturas mais altas. Espécies como *Senegalia polyphylla* (DC.) Britton mostraram resiliência às mudanças de temperatura, enquanto outras, como *Guazuma ulmifolia* Lam. mostraram sensibilidade a temperaturas elevadas. Esta investigação contribui para a compreensão dos potenciais impactos das alterações climáticas nos ecossistemas florestais e informa estratégias para a restauração e conservação das florestas.

Palavras-chave - aquecimento global; germinação de sementes; temperatura.

ABSTRACT

SHIGUEHARA, Ana Paula Ponce. Direct seeding seeds germination responses and their impacts on climate change. 2024. Defesa (Mestrado em Planejamento e Uso de Recursos Renováveis) – Universidade Federal de São Carlos, Sorocaba, 2024.

Climate change poses significant challenges to global ecosystems, particularly impacting seed germination in native forest species. This study investigates the germination response of 13 Brazilian forest species to simulated temperature regimes mimicking projected climate scenarios. Seeds were subjected to five temperature treatments, ranging from 25-50°C, and monitored for radicle emergence weekly. For the data analysis, each species included germination percentage (%G), Germination speed index (GSI) and Generalized Linear Mixed Models (GLMM). Preliminary results reveal varying germination responses across species, with some exhibiting decreased germination rates at higher temperatures. Species like *Senegalia polyphylla* (DC.) Britton showed resilience to temperature changes, while others, such as *Guazuma ulmifolia* Lam., displayed sensitivity to elevated temperatures. This research contributes to understanding the potential impacts of climate change on forest ecosystems and informs strategies for forest restoration and conservation.

Keywords – global warming; seed germination; temperature.

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SUMMARY

INTRODUCTION

Anthropogenic actions are responsible for altering the planet's climate dynamics due to deforestation and excessive gas emissions (ARORA, 2019). Predictions of rising temperatures for the future suggest various impacts on global climate and ecosystems (BONAN and DONAN, 2018; IPCC, 2023). These include more frequent and intense heat waves, changes in precipitation patterns leading to droughts in some regions and increased rainfall in others, shifts in agricultural productivity and crop yields, melting of polar ice caps and glaciers leading to sea level rise, disruptions to ecosystems and biodiversity, increased frequency and severity of extreme weather events such as storms, floods, and wildfires, and potential impacts on human health and well-being (BASKIN AND BASKIN, 2014; PRĂVĂLIE, 2018).

The effects of global warming extend beyond elevating mean temperatures but manifest in a decrease in the diurnal temperature range, where minimum temperatures rise at twice the rate of maximum temperatures (WALTHER et al., 2002). Moreover, on a seasonal scale, biological spring arrives earlier, while biological winter is delayed (PEÑUELAS; RUTISHAUSER; FILELLA, 2009; HUANG et al., 2017), altering the species reaching land and geographical distribution (DOLEZAL et al., 2020). More frequent and extended heat waves are also a consequence, which contributes to aggravating extreme events, increasing the fire risk, and generating eco-physiological stress and plant mortality (DOMEISEN et al., 2023).

Elevated temperatures associated with it can exceed the optimal range for the germination of certain plant species, leading to reduced germination rates or even failure to germinate altogether. In addition, changes in precipitation patterns also affect soil moisture levels, which are critical for seed germination. Extended periods of drought or irregular rainfall inhibit germination by preventing seeds from absorbing water or by causing seeds to germinate prematurely, only for seedlings to subsequently perish due to a lack of water (KLUPCZYŃSKA and PAWŁOWSKI, 2021; NAUTIYAL; SIVASUBRAMANIAM; DADLANI, 2023; LAMONT and PAUSAS, 2023).

Temperature is a critical factor in inducing seed germination and overcoming dormancy. It is considered the primary environmental cue regulating seed germination, with physiological dormancy, typically being overcome by specific temperature conditions. Seeds with physiological dormancy often require either moist, low-temperature conditions (1–10°C), known as cold stratification, or dry or moisture, high-temperature conditions (> 15°C), referred to as after-ripening or warm stratification. However, the degree of primary dormancy, duration, and specific conditions necessary to overcome it varies depending on the population and species (BASKIN and BASKIN, 2014; BANDERA et al., 2019).

Although several Savannah species have high abiotic stress tolerance, there still needs to be more understanding regarding the specific thresholds beyond which germination does not occur, nor is the phenotypic plasticity capacity of these forest species known (SULTAN, 2000; EMBRAPA, 2022). Recent studies found that some species increased auxin production, leading to elongation of the hypocotyl of the seedlings as temperatures rose (GRAY et al., 1998; SANTOS; CARDOSO; NIEVOLA, 2017; NIEVOLA et al., 2017), and regarding the temperature tolerance of forest, canopies found that the threshold temperature at which tropical trees maintain their photosynthetic structures functional is on average around 46.7 Cº (DOUGHTY et al., 2023). Nevertheless, there is still information missing about how this drastic increase in temperatures will influence the germination of tropical forest species, their threshold germination temperatures, and their future geographical distribution, especially considering the efforts put into restoration by direct sowing.

The demand for seeds on the market for direct sowing is fickle, and the action of community seed networks has facilitated an increase in production while at the same time centralizing the production process for the most commonly used species (RAUPP et al., 2020). In this scenario, knowing the germination responses of these most common and potential species used in direct seeding is vital. We hypothesize that the behavior of the species seeds changes with thermal heating. Based on this, this study aims to investigate the germination response to the factual increase in the global temperatures in native forest species and how it will alter the future floristic composition and distribution of forests, mainly those recovered using large common species for direct seeding.

MATERIAL AND METHODS

Species selection and seed sampling

Seeds from 13 target species for Brazilian forest restoration in the Atlantic Forest and Savannah biomes were chosen based on their potential for direct seeding (PIOTROWSKI et al., 2023) and seasonal availability. We selected the species based on their behavior of seed emergence, establishment, survival, and frequency of availability in the commercial forest seed market. These species are the most common taxa used in national forest restoration (CECCON; GONZÁLES; MARTORELL, 2016; PIOTROWSKI et al., 2023).

The selected species was *Jacaranda cuspidifolia* Mart. (Bignoniaceae), *Mabea fistulifera* Mart. (Euphorbiaceae), *Copaifera langsdorffii* Desf., *Mimosa bimucronata* (DC.) Kuntze, *Peltophorum dubium* (Spreng.) Taub., *Poecilanthe parviflora* Benth., *Senegalia polyphylla* (DC.) Britton & Rose. (Fabaceae), *Apeiba tibourbou* Aubl., *Ceiba speciosa* (A. St.-Hil.) Ravenna, *Guazuma ulmifolia* Lam. (Malvaceae), *Cedrela fissilis* Vell. (Meliaceae), *Psidium cattleyanum* Sabine (Myrtaceae), *Cecropia pachystachya* Trécul (Urticaceae). We obtained seeds from traditional communities linked to native seed networks, such as *Rede de Sementes do Xingu* and commercial producers. To represent the species and not only a population or patches, we obtained seeds from different producers and buyers, which collected samples from diverse matrices and populations in 2023. Seed samples for analysis were composed of a manual mix of various producers and provenances in the range of occurrence of each species.

Germination development under simulated temperature regimes

According to current climate change scenarios, we anticipate a temperature rise of about 1 to 4 °C higher by the end of the 21st century (IPCC, 2023) and beyond, considering heat wave scenarios in which the temperature can exceed 40 °C (INMET BRAZIL, 2024). We assume that in tropical and subtropical climates, the higher the altitude, the greater the temperature range; therefore, the conditions and alternating temperatures represent the average temperature range of the region (INMET BRAZIL, 2024).

Thus, seeking to explore the potential impacts of the increasing temperatures on seed germination, we tested five treatments: T1 (control)= 25 or 30º C with fix temperature for 24 hours according to the indication for each species by the Brazilian rules and proceeding of forest seed analysis (BRAZIL, 2009; 2010; 2011; 2013); and alternating temperatures every 12 hours: T2= 25-35 °C; T3= 30-40 °C; T4 = 35–45 °C; T5= 40-50 °C.

Laboratory treatments involved six replicates of 25 seeds per treatment, each on vermiculite substrate in transparent germination boxes with dimensions 11cm x 11cm x 3.5 cm (gerbox). We overcame dormancy when required by Brazilian rules and proceeding of forest seed analysis (BRAZIL, 2009; 2010; 2011; 2013). Treatments were carried out in temperature and light-controlled B.O.D. (Biological Oxygen Demand) seed germination chambers using a 12-h daily photoperiod under five temperatures and evaluated weekly during the extension period indicated by the Brazilian rules and proceeding of forest seed analysis (BRAZIL, 2009; 2013). We stored the seeds since receipt for six months to a year, and the experiments were conducted over six months, from November 2023 to March 2024.

All the parameters used to determine the pre-germination processes, the control temperature for each species, the duration of the germination experiment, and the irrigation were based on the "Instructions for analyzing seeds of forest species" (BRAZIL, 2013) and "Rules for seed analysis" (BRAZIL, 2009). Vermiculite was selected as a patterned substrate for its high porosity and capacity to retain water better than sand or germination paper. We moistened the substrate with distilled water to saturation (2.5 times the weight of the substrate), and irrigation was carried out according to demand since higher temperatures dry out the substrate more easily, requiring greater hydration.

Data analysis

Throughout the incubation period, we monitored seeds daily for radicle emergence within the initial week and weekly after that until the completion of each test, with germinated seeds promptly removed. The seed germination percentage was determined by the number of seeds radicle emergence (RE) under botanical criteria (LABOURIAU, 1983), which involved measuring radicle emission at 2mm.

We calculated each germination percentage, average, standard deviation, and coefficient of variation at the end of the test per treatment to evaluate seed germination responses to temperature. Subsequently, we calculated: (a) the germination percentage (%G) as radicle emergence; (b) Germination speed index (GSI) with the corresponding formula: $\sum$ (ni/ti), where ni is the number of seeds that germinated at a time 'i'; ti corresponds the time after the test was set up; (d) the analysis of factors affecting germination using a Generalized Linear Mixed Model (GLMM), incorporating both fixed effects (such as treatment conditions) and random effects (such as batch variability), to account for non-normal response distributions and complex data structures (ZUUR et al., 2009).

The ANOVA test, followed by Tukey's post-test at 5% probability, was used to check for differences between treatments. Generalized Linear Mixed Models (GLMM) were used to test the relationship between increasing temperatures and germination responses. The predictor variable was temperature, while the response variables were germination percentage and germination speed index (GSI). For germination percentage, we used the beta family due to the proportional nature of the data, and we used the Gaussian family for the germination speed index, which is suitable for continuous data. The significance level adopted was $p < 0.05$. We performed all the analyses using the RStudio program.

RESULTS AND DISCUSSION

We have results from thirteen species for seed radicle emergence - RE (Table 1). Nine species had germination rates over 50%: *Apeiba tibourbou, Cedrela fissilis, Copaifera langsdorffii, Guazuma ulmifolia, Jacaranda cuspidifolia, Mimosa bimucronata, Peltophorum dubium, Psidium cattleyanum, Senegalia polyphylla.* The species with the highest germination rates (≥ *80%*) in the control treatment (T1) were *S. polyphylla, P. cattleyanum, P. dubium, J. cuspidifolia,* and *C. langsdorffii,* demonstrating the quality of the lot.

Almost half of the species showed the highest germination rate in alternating temperatures of 25–35ºC (T2): *J. cuspidifolia*, *P. cattleyanum*, *A. tibourbou*, *P. parviflora, G. ulmifolia*, *M. fistulifera* and, *C. pachystachya,* possibly due to the acceleration of metabolic processes and the increase in temperature, which is still considered ideal for tropical seeds (Moore et al., 2021). Also, in BRANCALION, NOVEMBRE, and RODRIGUES (2010), *A.*

tibourbou was one of the species with optimal germination at alternating temperatures. In treatment 3 (T3) of altered temperatures of 30–40ºC, the only species with the highest rate was *M. bimucronata*, with 62.7% total germination.

The germination rate can provide us with a lot of information about the quality of the seeds. A high germination rate indicates that the seeds are viable and healthy, reflecting good storage in terms of time and method, following appropriate protocols (BRAZIL, 2009; 2013). In addition, this high rate suggests efficient handling during collection, with mature seeds in a good state of preservation and proper processing and conditioning (COPELAND and MCDONALD, 2001). Therefore, the germination rate not only assesses the viability of the seeds but also points to the effectiveness of the collection and storage procedures (FOWLER and MARTINS, 2001).

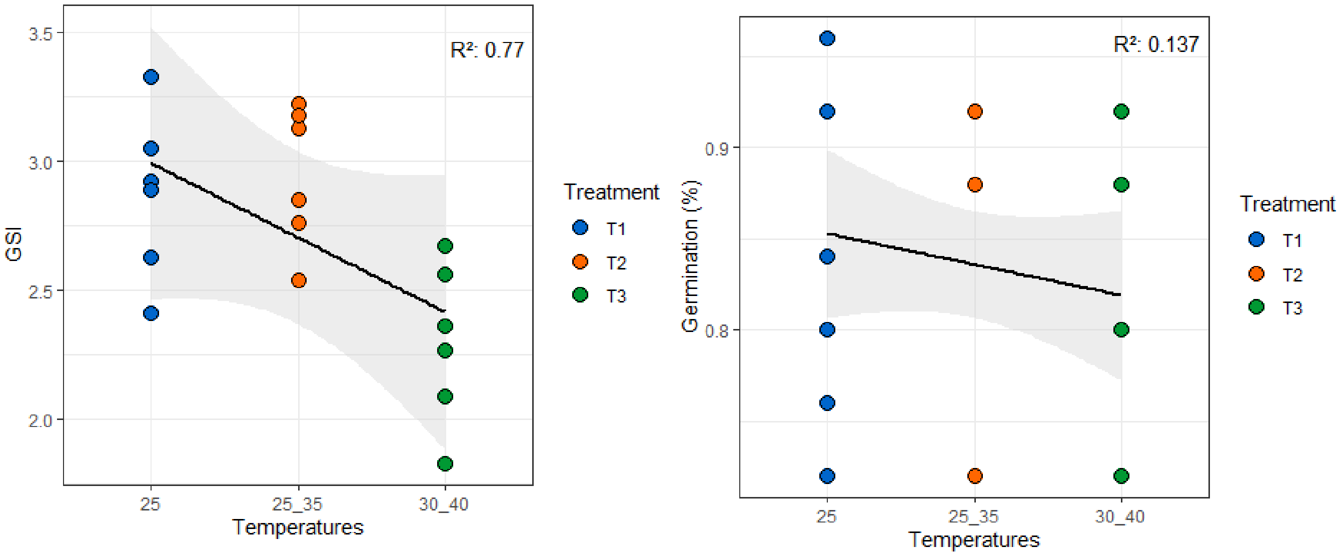
Table 1. Average percentage of seed radicle emergence with standard deviation (G%) and Germination Speed Index (GSI) at different temperatures for 13 species with potential for direct seeding. For each species and variable (G% and GSI) similar upper letters indicate no significative difference among the five treatments (p<0,05).

No. seed radicle emergence (%)											
Species	T1 (Control)			**T2 (25-35 ºC)**		**T3 (30-40 ºC)**		**T4 (35-45 ºC)**		**T5 (40-50 ºC)**	
	25 ºC	30 ºC									
	G%		GSI	G%	GSI	G%	GSI	G%	GSI	G%	**GSI**
Apeiba tibourbou	62±2.9 A	-	2.1 A	71.3±3.5 A	2.4 B	52±4 A	1.23 B	0	0	0	0
Cecropia pachystachya	25.3±3.1 A	-	0.78 B	42±2.4 B	0.38A	21.3±1.6 B	0.20 B	30±2 A	0.63B	0	0
Cedrela fissilis	61.3±1.6 A	-	1.98 A	32±4.2 A	1 A	0	0	0	0	0	0
Ceiba speciosa	46.7±6.5 A	-	1.2 A	14.7±3.4 A	0.4 A	2±0.8 B	0.35 A	0	0	0	0
Copaifera langsdorffii	87.3±1.1A	-	3.3A	86.7±0.5A	3.73A	84±1.8A	4A	13.3±1.5 B	0.57B	0	0
Guazuma ulmifolia	54±1.9A	-	2.4A	56.7±3.5A	2.56B	22±1.6B	0.54B	2.7±1.6B	0B	0	0
Jacaranda cuspidifolia	80±3.3A	-	4.72A	91.3±1.3A	3.8A	72±3A	2.24B	1.3±0.5B	0B	0	0
Mabea fistulifera	-	49.3±2.6A	1.9A	65.3±3.8A	3.28A	3.3±0.8B	0.3B	0	0	0	0
Mimosa bimucronata	-	57.3±2.9A	6.2B	44.7±2.1A	5.5A	62.7±3.8A	5.5A	32.7±2.3B	1.83A	0	0
Peltophorum dubium	92±2.4A	-	5.9A	84±1.8A	5.37A	82±1A	5.3A	5.3±2.3B	0.13B	0	0
Poecilanthe parviflora	-	42.7±1.1A	2.8A	52±3.9B	3B	41.3±2.1B	2.18B	16±1.7B	0.5B	0	0
Psidium cattleyanum	83.3±2.1A	-	2.9A	86±1.8A	3A	80.7±2A	2.3B	0	0	0	0
Senegalia polyphylla	88±1.6A	-	3.36A	72.7±1.6B	3A	81.3±3.1A	3.28A	80.7±1.9A	3A	0	0

P. cattleyanum, *C. langsdorffii*, and *P. dubium* had a germination rate of over 80% in treatments 1, 2, and 3 and occupy phytophysiognomies of the Cerrado, Atlantic Forest and Caatinga (REFLORA, 2024). Classified as orthodox seeds (CISNEIROS, 2003; CARVALHO, 2008), all species have high phenotypic plasticity: *P. dubium* adapts to different light levels (TROVATO et al., 2023), while *P. cattleyanum* has high morphoanatomical plasticity and different rates of stomatal coverage (França et al., 2021). *C. langsdorffii* exhibits significant variations in specific leaf area, palisade parenchyma thickness, and stomata density, contributing to its wide distribution and versatility (Siqueira et al., 2023). Morphologically, all three species exhibit tegument dormancy: *P. cattleyanum* has a rigid and impermeable seed tegument (TOMAZ et al., 2011), *C. langsdorffii* has tegument dormancy, overcome by scarification, and *P. dubium* also demonstrates physical dormancy (PEREIRA, LAURA, and SOUZA, 2013; MÜLLER, 2020). In general, these species showed the ability to germinate (G>80%) at high temperatures (40ºC), probably due to traits such as hard integuments, adaptable metabolism, and dormancy mechanisms, which could contribute to their successful germination in extreme conditions found in the phytophysiognomies where the species occur, such as droughts and occasional fires.

The comparisons reveal no significant differences (p=0.9033) in germination speed (GSI) of *P. cattleyanum* between T2 and T1 (Figure. 1, Table 1), but there are statistically significant differences between treatments (F=8.354; p=0.00365). Specifically, the T3-T1 (p= 0.0126) and T3-T2 (p=0.0053) were significantly different, indicating that the T3, with a peak temperature of 45ºC, can reduce germination speed compared to T1 and T2. For germination rate, the T1, T2, and T3 showed no statistically significant differences (F=0.633; p= 0.544), suggesting that the temperatures of these treatments affected germination speed but did not affect the germination rate of *P. cattleyanum* seeds.

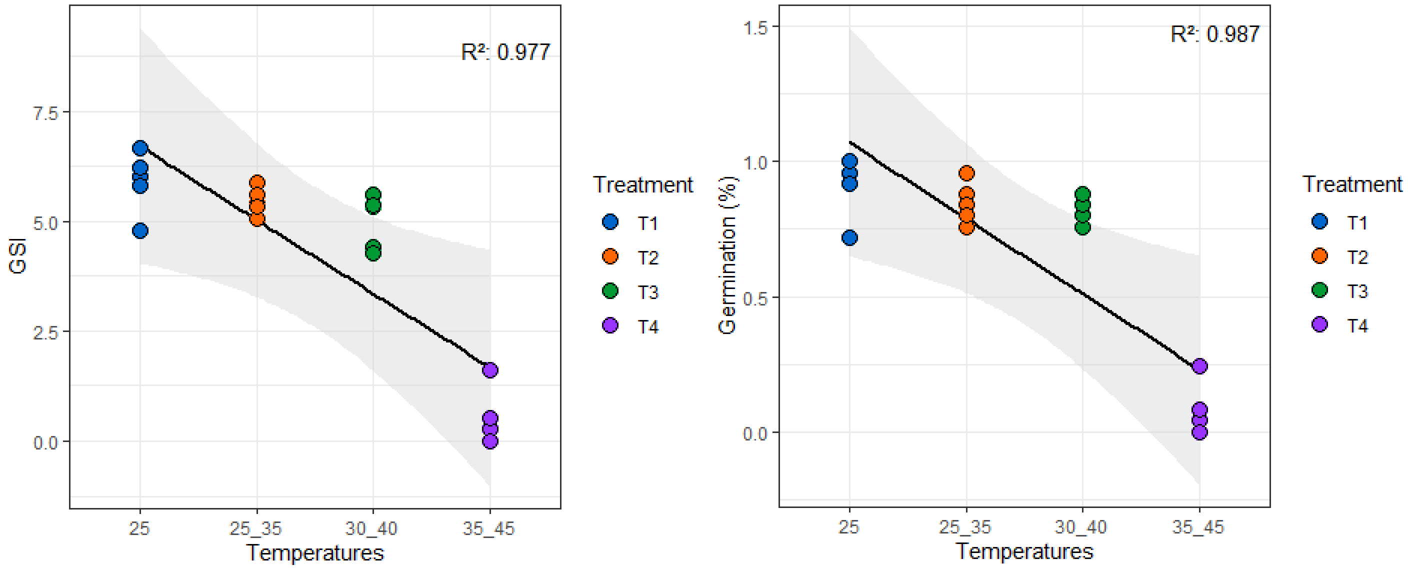
Figure 1. Germination Speed Index (GSI) of *Psidium cattleyanum* seeds subjected to treatments (T1, T2 and T3) as a function of temperature range (25°C, 25-35°C and 30-40°C); Germination percentages (%) of *Psidium cattleyanum* seeds subjected to treatments (T1, T2 and T3) as a function of temperature range (25°C, 25-35°C and 30-40°C). The treatments are represented by different colors: blue (T1), orange (T2) and green (T3).



Source: elaborated by the authors.

The GSI and germination rate indicate that the treatments have significantly different effects on *P. dubium* seeds (Figure. 2). For germination speed, the comparisons between T2-T1 (p=0.4904), T3-T1 (p= 0.0653), and T3-T2 (p=0.6178) are not significant, suggesting that there are no relevant statistical differences in these pairs of treatments. However, the comparisons involving T4 (T4-T1, T4-T2, and T4-T3) are highly significant (F= 133.2; p= 2.19e-13), indicating that the T4 treatment results in a significantly lower germination speed compared to T1, T2, and T3. T4 results suggest that the GSI is directly related to increasing temperatures, a finding consistent with the results of PEREIRA et al. (2013). Similarly, for the germination rate, the T2-T1, T3-T1, and T3-T2 comparisons also showed no significant differences, while T4 shows significantly lower germination compared to T1, T2, and T3 (F= 146.3; p=8.99e-14). T4 has a detrimental impact on the speed and rate of germination of *P. dubium* seeds, while T1, T2, and T3 do not differ.

Figure 2. Germination Speed Index (GSI) of *Peltophorum dubium* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C); Germination percentages (%) of *Peltophorum dubium* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C). The treatments are represented by different colors: blue (T1), orange (T2), green (T3) and purple (T4).

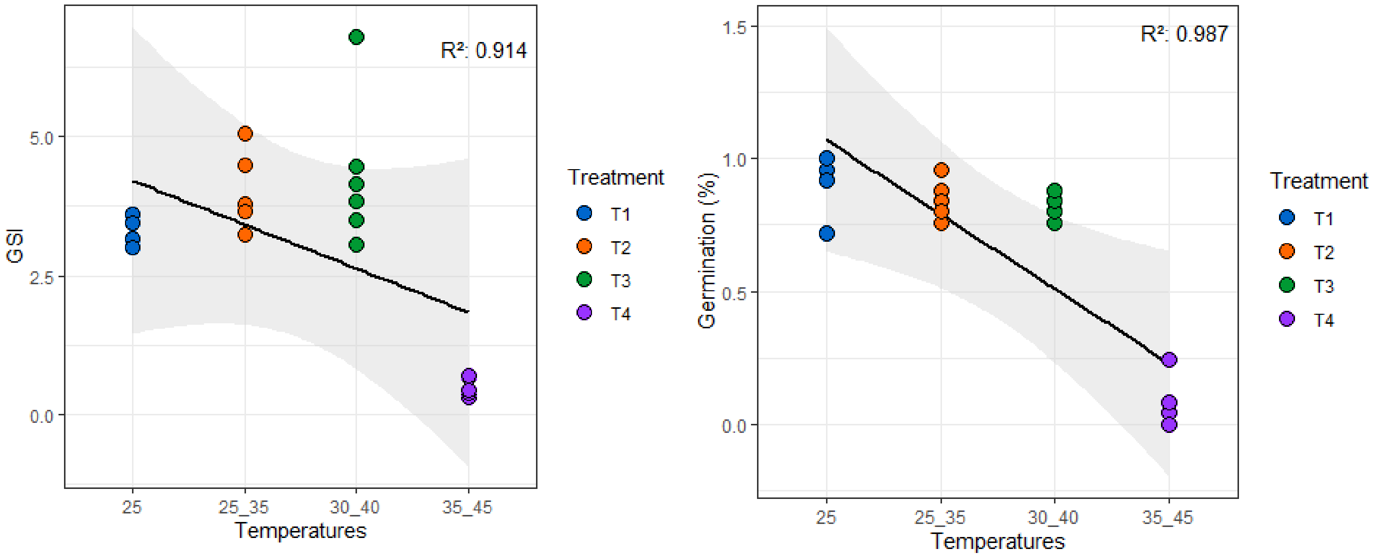


Source: elaborated by the authors.

For *C. langsdorffii*, both the GSI (F=30.97; p=1.03e-07) and the seed germination rate (F=277.8; p=2e-16) indicate significant differences between the treatments (Figure. 3). For the GSI, the comparisons between T2-T1 and T3-T1 reveal no significant statistical differences, suggesting that the germination rate between these treatments and the T1 treatment is similar. However, the T4-T1, T4-T2, and T4-T3 comparisons are significant, indicating that the T4 treatment significantly reduces germination speed compared to T1, T2, and T3. Therefore, the T4 treatment has an unfavorable effect on germination speed, while T1, T2, and T3 show no significant differences. As for the germination rate, the p-value (< 2e-16) suggests substantial statistical differences between the treatments, with T4 showing a significantly lower effect on germination compared to T1, T2, and T3. Thus, T4 is ineffective in promoting rapid germination of *C. langsdorffii* seeds, while T1, T2, and T3 have similar effects in germination speed and rate. These results indicate that the T4 treatment is less suitable for both the speed and rate of seed germination.

Figure 3. Germination Speed Index (GSI) of *Copaifera langsdorffii* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C); Germination percentages (%) of *Copaifera langsdorffii* seeds subjected to treatments (T1, T2, T3, and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C). The treatments are represented by different colors: blue (T1), orange (T2), green (T3) and purple (T4).

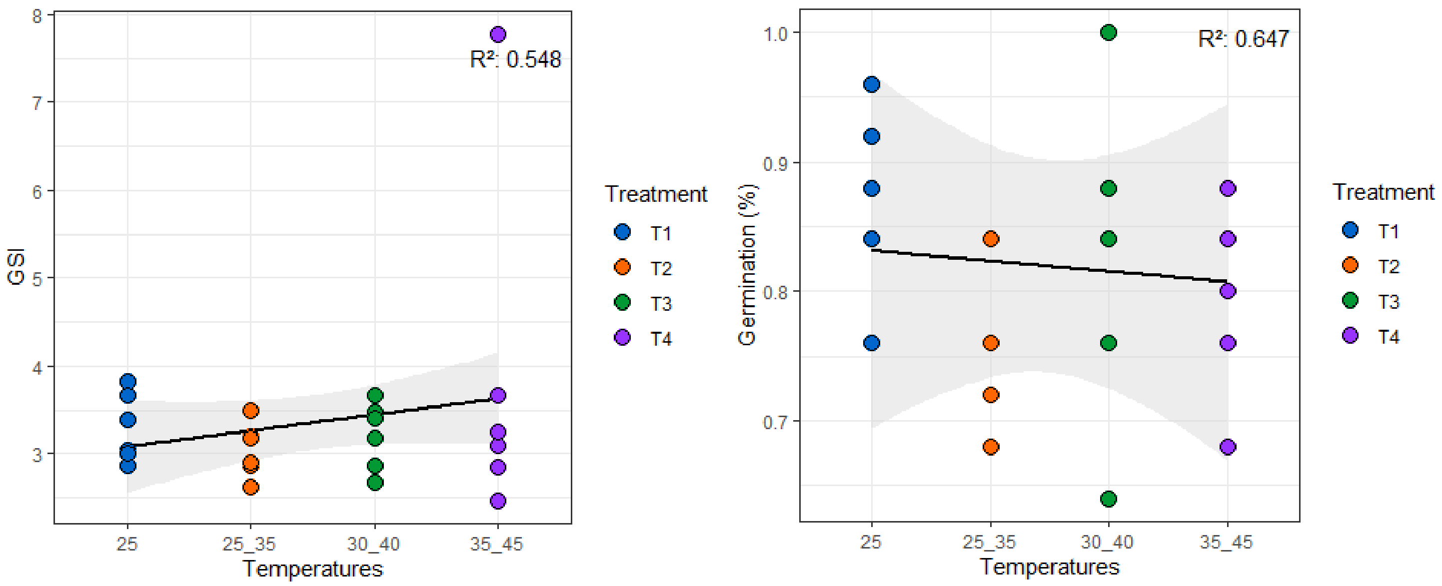
Source: elaborated by the authors.



Source: elaborated by the authors.

Senegalia polyphylla was the only species with a consistently high germination rate until T4, achieving a germination percentage of around 80% in all treatments except T5. This germination percentage is also reported in other seed viability studies, such as which noted an 88% germination rate at 30ºC. *S. polyphylla* also showed no significant difference in germination speed between treatments (F=0.694; p=0.567) (Figure. 4), indicating that temperature had no relevant effect on this factor. However, the treatments had significantly different effects on the germination of the species' seeds (F=3.111; p=0.0494). When comparing T2 and T1, there was a significant difference in germination (adjusted p-value of 0.0299), suggesting that T2 resulted in significantly lower germination than T1. Comparisons between the other treatments showed no statistically significant differences, indicating no notable variations in germination between temperatures. According to HONDA, PILON, and DURIGAN (2019), the seedlings demonstrated a remarkable ability to survive under competition for water, which likely contributes to the species' high ecological and morphological plasticity and wide geographical distribution (FERNANDES, 2022; SENA, 2022). Widely used in projects to restore degraded areas due to its hardiness and rapid growth (CARVALHO et al., 2008), *S. polyphylla* is a pioneer species that allocates resources to dispersing large quantities of seeds, exhibiting a remarkable percentage of seed. Empty seeds were present in only one of the sampled matrices, and even seeds with minor damage or malformations could generate normal seedlings (GIBBERT, 2019). All these factors combined prove the capacity of the species to survive environmental stress, and these results may indicate a future *Senegalia polyphylla* was the only species with a consistently high germination rate until T4, achieving a germination percentage of around 80% in all treatments except T5. Other seed viability studies also report this germination percentage, such as LIMA and CUNHA (2019), which noted an 88% germination rate at 30ºC. *S. polyphylla* also showed no significant difference in germination speed between treatments (F=0.694; p=0.567) (Figure. 4), indicating that temperature had no relevant effect on this factor. However, the treatments had significantly different effects on the germination of the species' seeds (F=3.111; p=0.0494). When comparing T2 and T1, there was a significant difference in germination (adjusted p-value of 0.0299), suggesting that T2 resulted in significantly lower germination than T1. Comparisons between the other treatments showed no statistically significant differences, indicating no notable variations in germination between temperatures. According to HONDA, PILON, and DURIGAN (2019), the seedlings demonstrated a remarkable ability to survive under competition for water, which likely contributes to the species' high ecological and morphological plasticity and wide geographical distribution (FERNANDES, 2022; SENA, 2022). Widely used in projects to restore degraded areas due to its hardiness and rapid growth (CARVALHO et al., 2008), *S. polyphylla* is a pioneer species that allocates resources to dispersing large quantities of seeds, exhibiting a remarkable percentage of seeds classified as full. Empty seeds were present in only one of the sampled matrices, and even seeds with minor damage or malformations could generate normal seedlings (GIBBERT, 2019). All these factors combined prove the capacity of the species to survive environmental stress, and these results may indicate a future widespread distribution of this species over others.

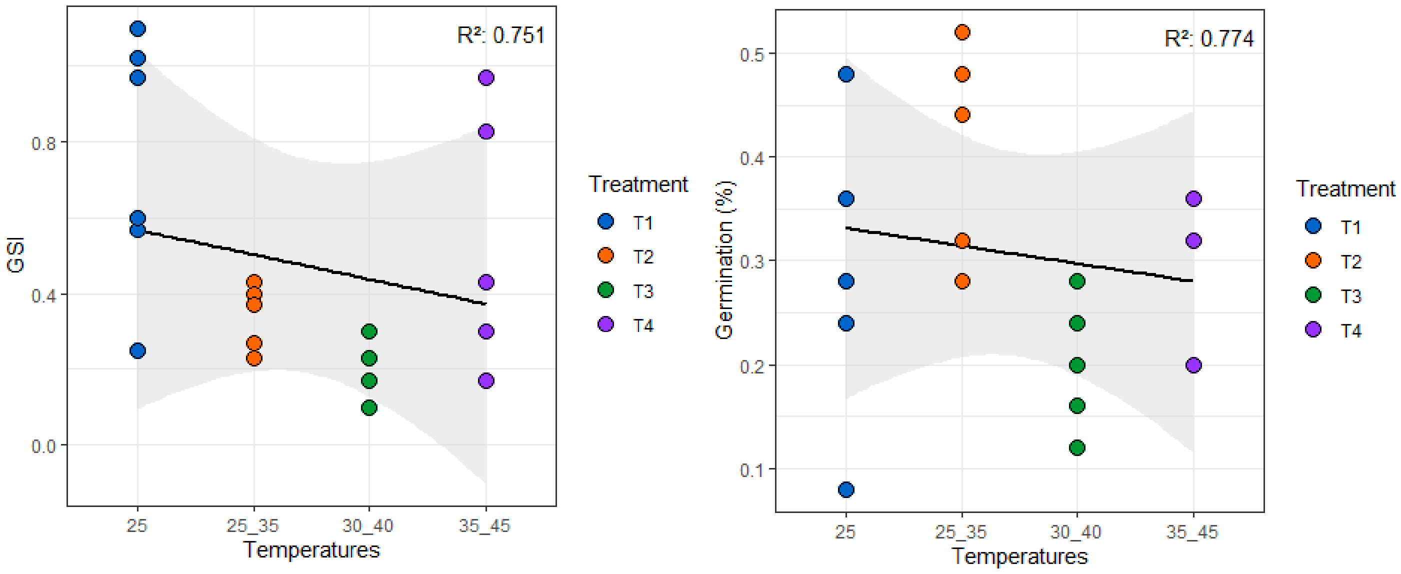
Figure 4. Germination Speed Index (GSI) of *Senegalia polyphylla* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C); Germination percentages (%) of *Senegalia polyphylla* seeds subjected to treatments (T1, T2, T3, and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C). The treatments are represented by different colors: blue (T1), orange (T2), green (T3) and purple (T4).



Source: elaborated by the authors.

Different temperatures affect the speed (F=6.457; p=0.0031) and germination rate (F=4.513; p= 0.0142) of *C. pachystachya* seeds differently (Figure. 5). Specifically, T3 showed a significantly different germination speed compared to T1 (p=0.0032), and T4 showed significant differences compared to T3 (p= 0.0425). In addition, the comparison between T3 and T2 revealed a substantial difference in germination rate (adjusted p-value of 0.0079), with T3 showing significantly lower germination than T2 (p-value < 0.01). Other comparisons between treatments showed no statistically significant differences.

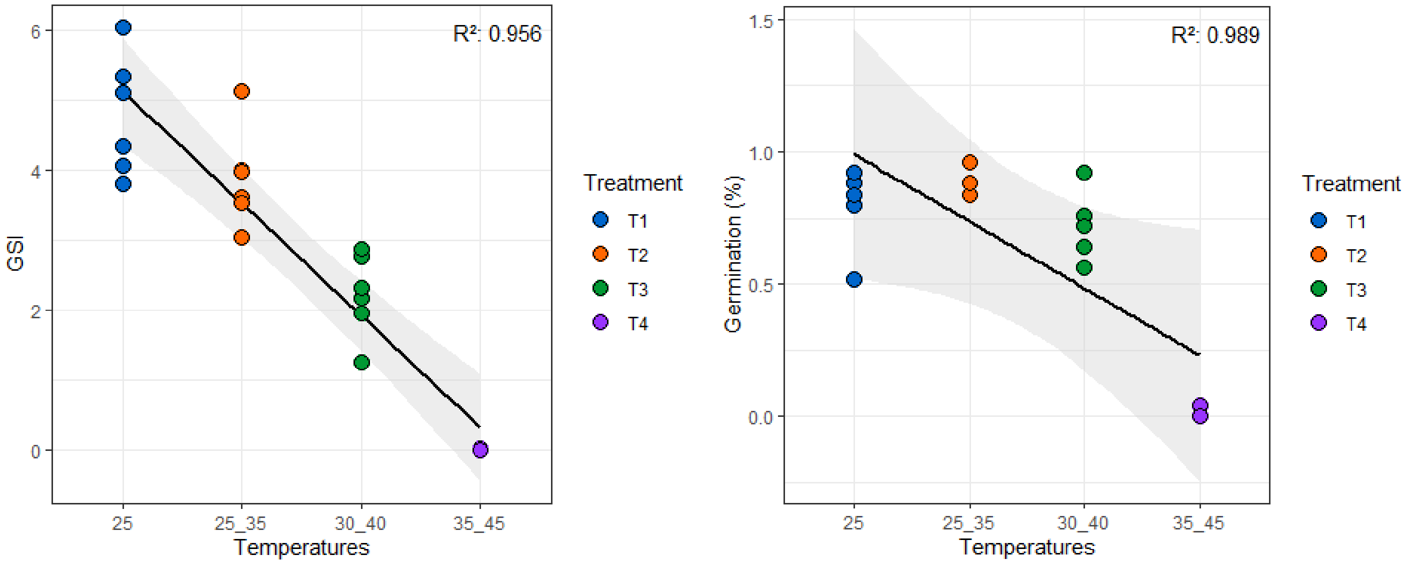
Figure 5. Germination Speed Index (GSI) of *Cecropia pachystachya* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C); Germination percentages (%) of *Cecropia pachystachya* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C). The treatments are represented by different colors: blue (T1), orange (T2), green (T3) and purple (T4).



Source: elaborated by the authors.

The results indicate that the treatments have significantly different effects on the speed (F=66.87; p=1.33e-10) and rate of germination (F=103.2; p=2.43e-12) of *J.cuspidifolia* seeds (Figure. 6). Concerning germination speed, T4 differ significantly from T1(p-value < 0.001), indicating that T4 have very different and more minor effects on germination speed compared to T1. Between T3 and T2 (p= 0.0134), T4 and T2 (p-value < 0.001), and T4 and T3 (p-value < 0.001), the differences are highly significant, with T4 showing the most negative effect on germination speed and being significantly different from all the other treatments. On the other hand, T2 is not substantially different from T1 (p=0.2204) but shows notable differences compared to T3 and T4. As for the germination rate, the T4 treatment also differs significantly from all the others (T1, T2, and T3), suggesting that T4 negatively affects seed germination (p-value < 0.001). The difference between T2 and T3 is significant (p=0.0009498), indicating that these two treatments have different effects on germination, while comparisons between T2 and T1 (p=0.0963) and T3 and T1 (p=0.0000043) show no significant differences. These results show that treatment T4 is the least effective in promoting the germination of *J.cuspidifolia* seeds.

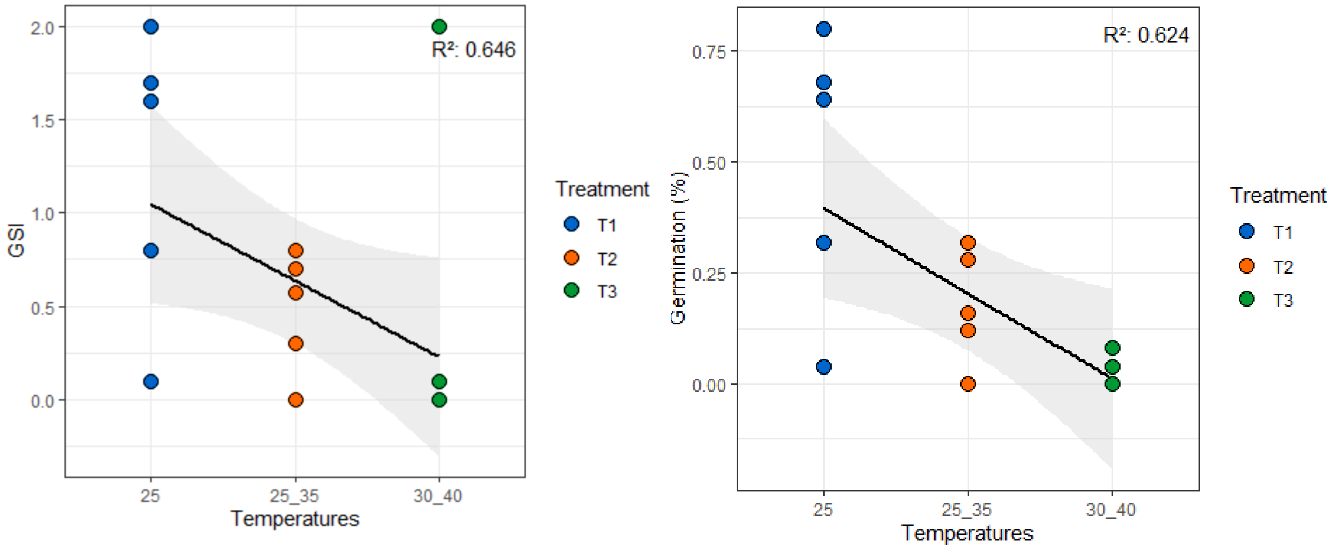
Figure 6. Germination Speed Index (GSI) of *Jacaranda cuspidifolia* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C); Germination percentages (%) of *Jacaranda cuspidifolia* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C). The treatments are represented by different colors: blue (T1), orange (T2), green (T3) and purple (T4).



Source: elaborated by the authors.

There is a tendency for the treatments to differ in terms of the germination speed of *C. speciosa* seeds. However, the difference is not statistically significant at the 5% level, (F=2.937; p=0.0839), as confirmed by Tukey's test. Therefore, based on these data, we cannot conclude that the different treatments have different effects on the germination speed of *C. speciosa* seeds (Figure. 7). Significant differences were observed in the germination rate between treatments for this species, (F=9.369; p=0.00229), showing no significant difference between T2- T3 (p=0.4763), and T2 - T3 have significantly lower effects on germination compared to T1 (p=0.0226; p= 0.0021).

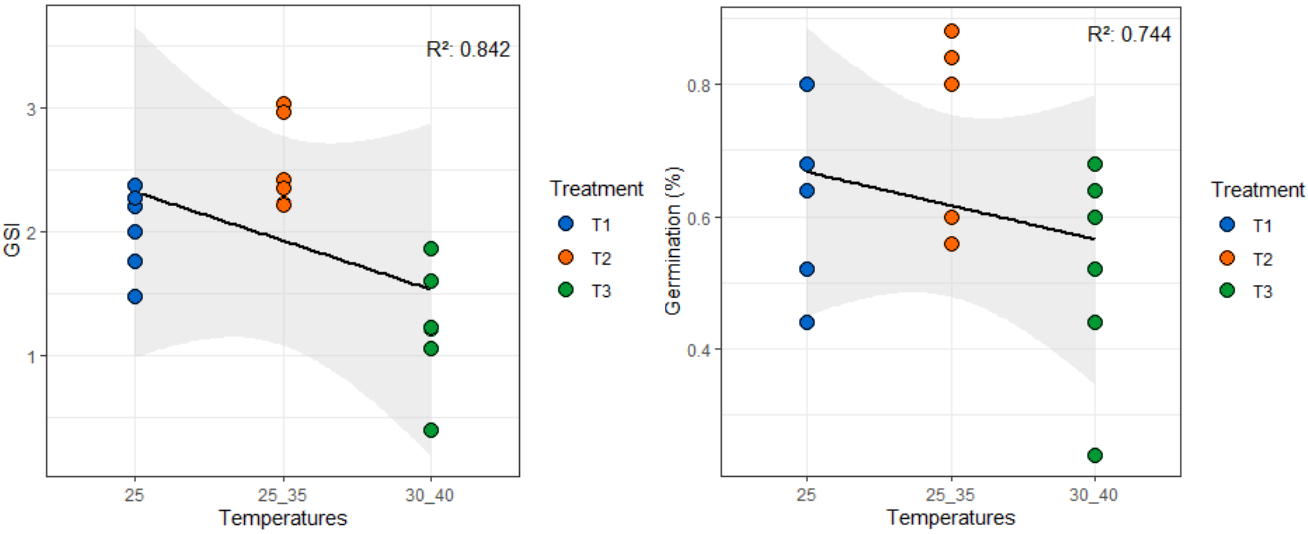
Figure 7. Germination Speed Index (GSI) of *Ceiba speciosa* seeds subjected to treatments (T1, T2 and T3) as a function of temperature range (25°C, 25-35°C and 30-40°C); Germination percentages (%) of *Ceiba speciosa* seeds subjected to treatments (T1, T2 and T3) as a function of temperature range (25°C, 25-35°C and 30-40°C). The treatments are represented by different colors: blue (T1), orange (T2) and green (T3).



Source: elaborated by the authors.

The results of the analysis of the germination speed index (GSI) and the germination rate of the *A. tibourbou* seeds indicate significant differences in the GSI between the treatments (Figure. 8). The p-value (0.000236) is much lower than 0.05, suggesting that at least one of the treatments has a significantly different effect on the GSI. Comparisons between T2 and T1 (p=0.1048) show no significant difference, indicating that these treatments have similar effects on GSI. However, T3-T1 (p= 0.0125) and T3-T2 (p= 0.0002) comparisons are substantial, revealing that the T3 results in a significantly lower GSI than T1 and T2. It suggests that T3 is ineffective in promoting the germination speed of *A. tibourbou* seeds, while T1 and T2 show no significant differences. Regarding the germination rate, we found no significant differences (F=2.706; p=0.0992) between the treatments. Among the species for which alternating temperatures were exclusively indicated as optimal, species typically at the beginning of the forest succession stood out (BRANCALION, NOVEMBRE, and RODRIGUES 2010).

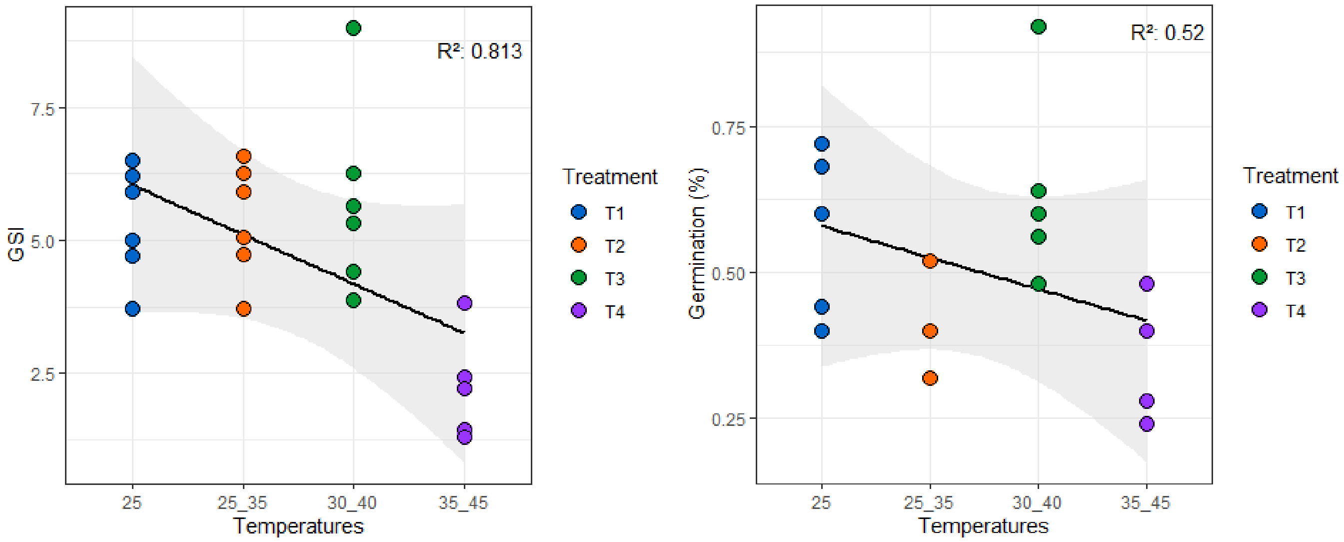
Figure 8. Germination Speed Index (GSI) of *Apeiba tibourbou* seeds subjected to treatments (T1, T2 and T3) as a function of temperature range (25°C, 25-35°C and 30-40°C); Germination percentages (%) of *Apeiba tibourbou* seeds subjected to treatments (T1, T2 and T3) as a function of temperature range (25°C, 25-35°C and 30-40°C). The treatments are represented by different colors: blue (T1), orange (T2), and green (T3).



Source: elaborated by the authors.

M. bimucronata also revealed significant differences between the treatments when analyzing the germination speed index (GSI) and the germination rate of the seeds (Figure. 9). The p-value (3.37e-12) indicates that at least one of the treatments has a significantly different effect on the GSI. The comparisons show that T2, T3, and T4 have considerably lower impacts on GSI compared to T1 (p-value < 0.001), while there are no significant differences in GSI between treatments T2, T3, and T4 (p-value > 0.5). T1 may be more effective in promoting the germination speed of *M. bimucronata* seeds, while T2, T3, and T4 have similar and less pronounced effects. Concerning germination rate, (F=7.763; p=0.00125), T4 may be less effective in promoting germination (p-value < 0.001), while T1, T2, and T3 had similar effects on germination rate.

Figure 9. Germination Speed Index (GSI) of *Mimosa bimucronata* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C); Germination percentages (%) of *Mimosa bimucronata* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C). The treatments are represented by different colors: blue (T1), orange (T2), green (T3) and purple (T4).

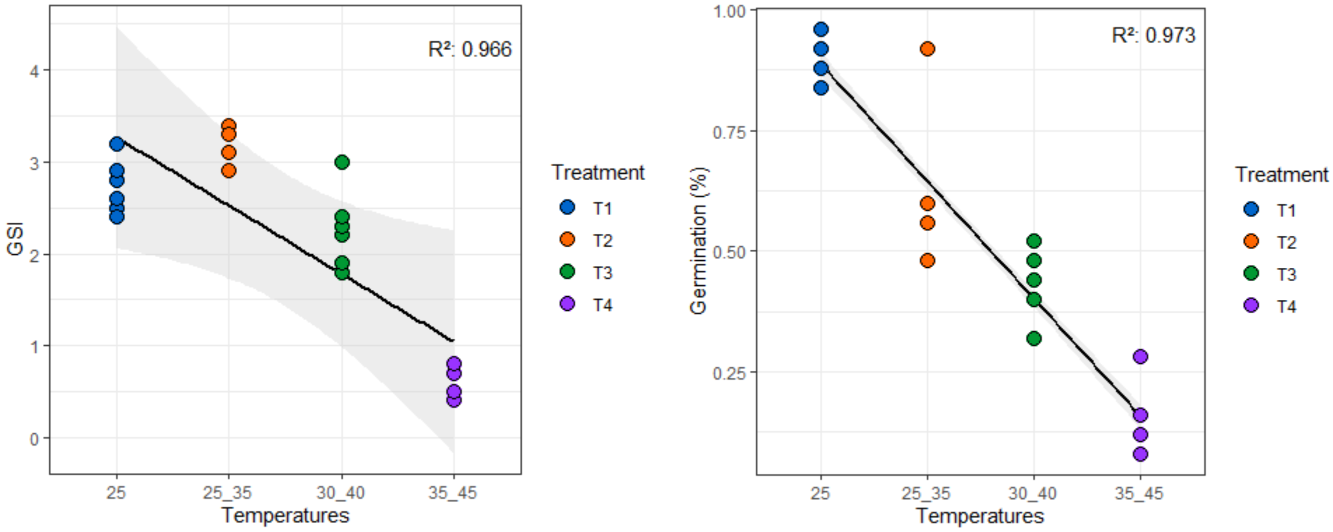


Source: elaborated by the authors.

The results of the analysis of the GSI (F=87.82; p=1.09e-11) and the germination rate (F=61.24; p=2.94e-10) of *P. parviflora* seeds show significant differences between the treatments (Figure. 10). The T4-T1 comparison revealed a highly significant difference (p-value < 0.001), indicating that the T4 treatment results in a significantly lower GSI compared to T1. In addition, T3 also shows a substantially lower GSI than T2 (p=0.0006049), and T4 has a considerably lower GSI compared to T2 and T3 (p-value < 0.001). The comparison between T2 and T1 is insignificant (p=0.2034992), suggesting no substantial difference between these treatments, while the difference between T3 and T1 is marginally non-significant (p=0.0570710). As for the germination rate (p-value 2.94e-10), there are statistically significant differences between all treatments. Comparisons between all treatments are significant (p-value

< 0.01), and T4 results in the lowest germination rate, followed by T3, T2, and T1, with the highest rate.

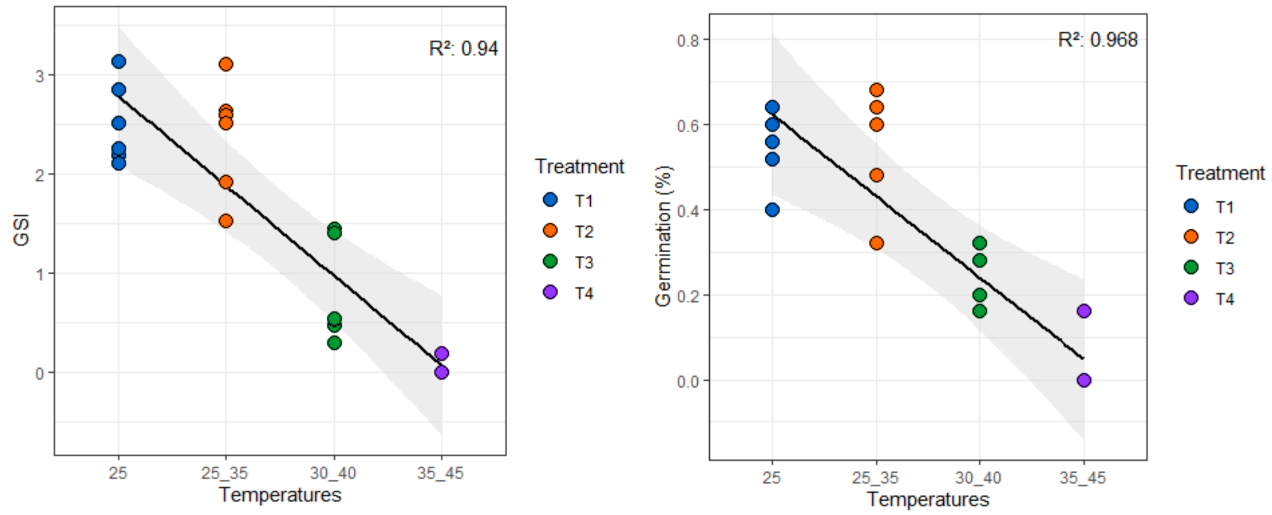
Figure 10. Germination Speed Index (GSI) of *P. parviflora* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C); Germination percentages (%) of *P. parviflora* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C). The treatments are represented by different colors: blue (T1), orange (T2), green (T3) and purple (T4).



Source: elaborated by the authors.

G. ulmifolia obtained significant differences between the treatments when analyzing the Germination Speed Index (GSI) (F=47.31; p=2.88e-09) and the germination rate of the seeds, (F=45.87; p=3.77e-09) (Figure. 11). For the GSI, the T4-T1 comparison revealed a highly significant difference (p-value < 0.001), showing that the T4 treatment resulted in a significantly lower GSI than T1. Similar comparisons were observed for T3-T1, T4-T2, T3-T2 (p-value < 0.001), and T4-T3, (p=0.0339020), all indicating that T4 and T3 have significantly lower GSI when compared to T1 and T2. However, the T2-T1 comparison showed no significant differences (p=0.9552367). On germination, (p-value 3.77e-09) indicates statistically significant differences between the treatments. Comparisons between the treatments showed that T4 results in significantly lower germination than the other treatments, and T3 also results in lower germination compared to T1 and T2 (p-value < 0.01). The T2-T1 comparison showed no significant differences (p=0.9604755). In experiments conducted with 18 species, Pearson et al. (2002) found that *G. ulmifolia* did not show a significant difference in germination rate between treatments with and without light, indicating that the species is not photoblastic. In thermal variation tests, *G. ulmifolia* showed a positive response to the amplitude of temperature variation, so that, up to a moderate variation (in the range of 0 to 16.78 °C), germination increased, suggesting that the species uses this variation, a typical signal of large gaps in the canopy, as a stimulus to germinate. Above this threshold, the response became idiosyncratic, indicating sensitivity to more extreme thermal conditions.

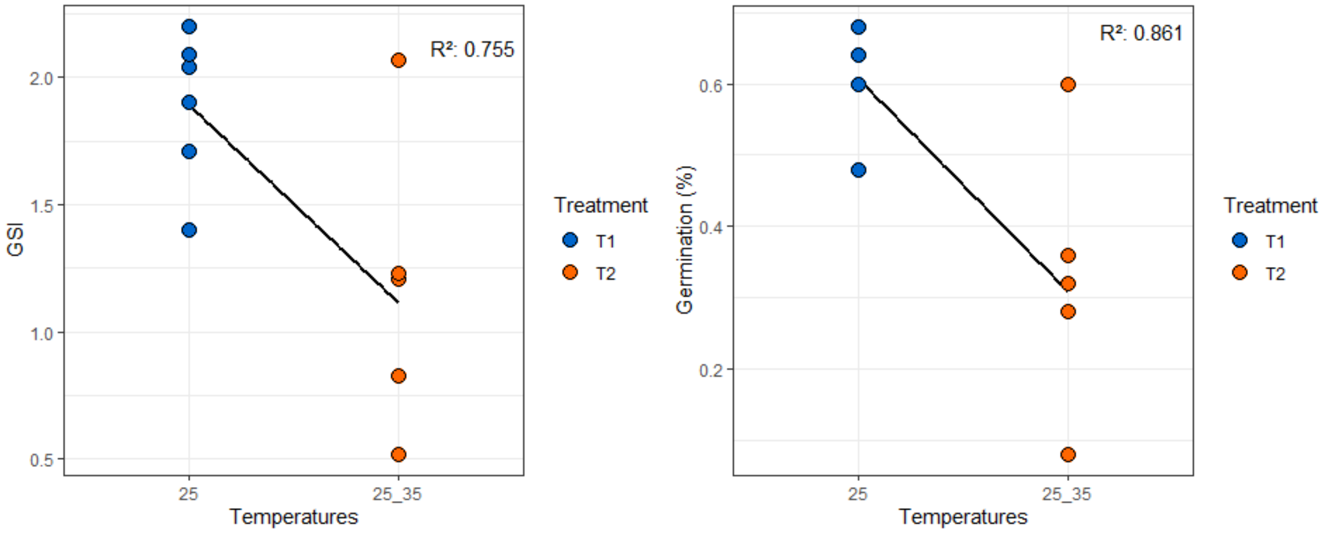
Figure 11. Germination Speed Index (GSI) of *Guazuma ulmifolia* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C); Germination percentages (%) of *Guazuma ulmifolia* seeds subjected to treatments (T1, T2, T3 and T4) as a function of temperature range (25°C, 25-35°C, 30-40°C and 35-45°C). The treatments are represented by different colors: blue (T1), orange (T2), green (T3) and purple (T4).



Source: elaborated by the authors.

C. fissilis also obtained significant differences between the treatments when analyzing the Germination Speed Index (GSI) and the germination rate of the seeds (p-value < 0.01) (Figure. 12). The comparison between T1 and T2 shows a significant difference, with T1 having a higher GSI (p= 0.011361) than T2. All the tests confirmed this difference's significance, indicating that the T1 treatment is more effective in promoting germination speed than T2. Regarding germination, T1 showed a significantly higher germination rate than T2 (p=0.0027245), and this difference was confirmed in all the tests, reinforcing that T1 is more effective in promoting the germination of *C. fissilis* seeds.

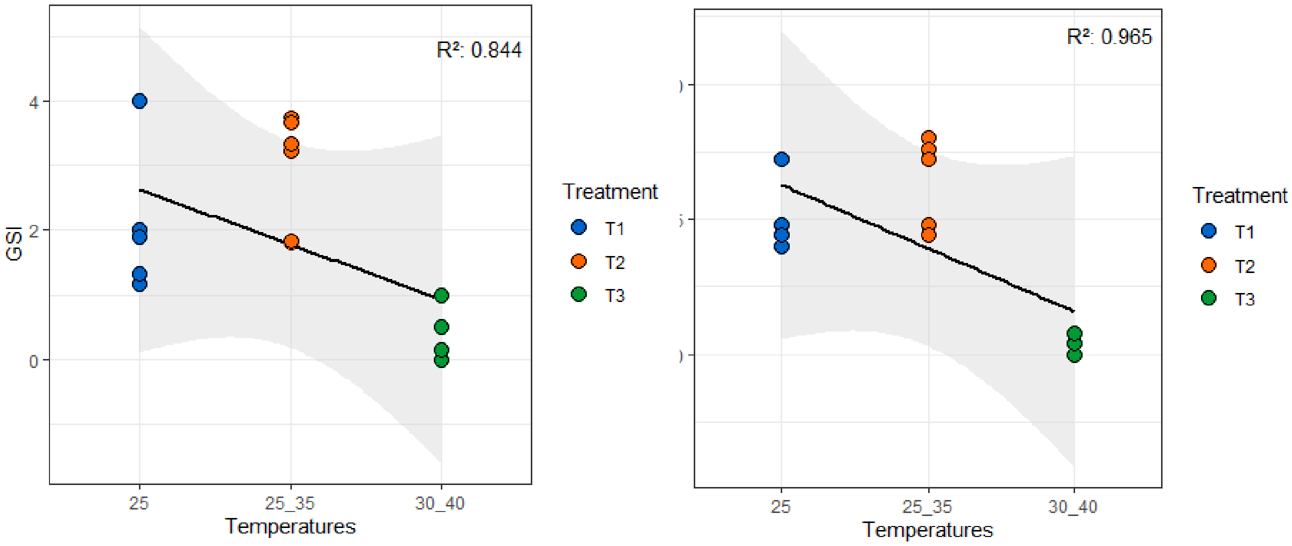
Figure 12. Germination Speed Index (GSI) of *Cedrela fissilis* seeds subjected to treatments (T1 and T2) as a function of temperature range (25°C and 25-35°C); Germination percentages (%) of *Cedrela fissilis* seeds subjected to treatments (T1 and T2) as a function of temperature range (25°C and 25-35°C). The treatments are represented by different colors: blue (T1) and orange (T2).



Source: elaborated by the authors.

M. fistulifera showed statistically significant differences in germination between the treatments, (F=49.6; p=2.45e-07). The comparisons show that T3 has a considerable difference from T1 and T2 (p-value < 0.001), with a marked reduction in the germination rate (Figure. 13). The difference between T2 and T1 is not significant at the 0.05 level but can be considered marginally significant. As for the germination rate analysis (GSI) (F=15.64; p=0.000214), the T2-T1 comparisons are not substantial (p=0.1774276), but T3-T1 and T3-T2 are significant (p-value < 0.01), showing that the T3 treatment has a lower GSI compared to T1 and T2.

Figure 13. Germination Speed Index (GSI) of *Mabea fistulifera* seeds subjected to treatments (T1, T2 and T3) as a function of temperature range (25°C, 25-35°C and 30-40°C); Germination percentages (%) of *Mabea fistulifera* seeds subjected to treatments (T1, T2 and T3) as a function of temperature range (25°C, 25-35°C and 30-40°C). The treatments are represented by different colors: blue (T1), orange (T2), and green (T3).



Source: elaborated by the authors.

For most of the species studied, it is possible to observe a decrease in germination with increasing temperatures, given that in T4 of alternating temperatures of 35–45ºC, germination in several species tends to be lower, such as *G. ulmifolia* and *J. cuspidifolia*, with only 2.7% and 1.3% of germinated seeds, or equal to zero, such as *A. tibourbou*, *C. speciosa*, M. *fistulifera*, and *P. cattleyanum*. Of all the species tested, *S. polyphylla* showed the most significant resistance/resilience to increasing temperatures in the treatments tested. The species showed uniform germination up to treatment 4 with a maximum temperature of 45 °C.

Expected species performance in ecological restoration a scenario of climatic change

As global temperatures rise, regions relying on *P. dubium*, *G. ulmifolia* and *J. cuspidifolia* for ecological restoration will also likely experience increased heat levels. If temperatures reach 35 to 45ºC, germination success for these species may decrease, leading to fewer seedlings and reduced restoration effectiveness. Higher temperatures could also disrupt the timing of seed germination and seedling establishment, potentially causing mismatches with resource availability and further impacting restoration success. Areas currently suitable for these species might become less viable, necessitating a shift to cooler regions. While *P. dubium, G. ulmifolia* and *J. cuspidifolia* can germinate under stress conditions (35ºC to 45ºC), selective pressure may lead to adaptations over time.

However, this process may not keep pace with rapid climate changes. Reduced germination success and establishment could impact biodiversity and ecosystem structure, mainly if these species are key to their habitats. *C. fissilis* does not show any germination after treatment 3 (maximum of 40 °C). For *P. cattleyanum*, germination rates remain stable up to 40ºC, but extreme temperatures (>40ºC) may hinder seedling establishment and competitive ability. Restoration efforts should avoid extreme heat to ensure successful germination. In summary, climate change poses challenges for the germination and establishment of *P. dubium,* M. *fistulifera, C. speciosa, A. tibourbou, C. fissilis,* and *P. cattleyanum* in restoration projects. Practitioners may need to adjust their strategies, such as selecting more temperature-tolerant species or adjusting timing, to achieve successful restoration outcomes.

For most species studied, it is possible to observe a decrease in germination with increasing temperatures. T4 of alternating temperatures of 35–45ºC, germination in several species tends to be lower (under 10% germination), such as *P. dubium*, *G. ulmifolia* and *J. cuspidifolia*, with only 5.3%, 2.7% and 1.3% of germinated seeds, or equal to zero, such as *A. tibourbou, C. speciosa*, M. *fistulifera, C. fissilis,* and *P. cattleyanum*. suggesting/demonstrationg low tolerance to extreme temperatures.

Of all the species tested, *S. polyphylla* showed the most resistance to increasing temperatures in the treatments. *Senegalia polyphylla* showed high germination percentages around 80%, even at temperatures of 35-45ºC (T4), indicating a strong resilience to high temperatures, which aligns with findings from LIMA and CUNHA (2019), who reported an 88% germination rate at 30ºC. Additionally, no significant difference in germination speed was observed across treatments, suggesting temperature does not affect this aspect significantly. *S. polyphylla* may continue to germinate effectively even under extreme heat conditions, making it a suitable candidate for restoration projects in regions experiencing higher temperatures due to climate change. Consistent germination percentages across various temperatures suggest that *S. polyphylla* can support population stability and play a significant role in ecosystem restoration. However, given its high germination plasticity, caution is needed to avoid the species' potential dominance. The genus *Senegalia* Raf., comprising 60 species widely distributed across all phytogeographic domains in Brazil, offers a promising opportunity for testing germination resistance under high-temperature conditions (REFLORA, 2024).

Senegalia polyphylla and *Mimosa bimucronata* show germination consistency across different treatments, indicating plasticity to cope with temperature variations. *Senegalia polyphylla* maintains germination above 70% in T1, T2, T3, and T4, demonstrating the potential for environments with greater temperature amplitudes. Although lower, other species such as *C. pachystachya*, *C. langsdorffii, and P. parviflora* can successfully germinate at T4.

The sharp reduction in germination, with 21.3% in T3 (30-40°C), suggests that *C. pachystachya* is sensitive to higher temperatures, which may limit its germination in environments with heat peaks. T2 (25-35°C) is the most favorable for the germination of *C. pachystachya*, with the highest average germination percentage (42%). From an ecological perspective, several articles investigating the influence of endozoochory on the germination of the species indicate that passage through the digestive tract of animals such as bats would increase the germination rate of *C. pachystachya* (Carvalho, Raizer, and Fischer, 2017; Carvalho, Raizer, and Fischer, 2020). The use of acid to overcome the dormancy of these seeds is also indicated by the Brazilian rules and proceeding of forest seed analysis as an optional method (BRAZIL, 2009; 2010; 2011; 2013). In other words, in ecological restoration projects, it is crucial to consider the temperature range to optimize the germination of *C. pachystachya*, among pioneer species and their ecological relationships with other dispersing species.

High GSI species, such as *Mimosa bimucronata* and *Peltophorum dubium*, are crucial in providing rapid initial cover, playing a key role as pioneers in stabilizing the soil, reducing erosion, and creating conditions conducive to the establishment of slower-growing species. Conversely, species with low GSI, such as *Ceiba speciosa*, *Guazuma ulmifolia*, and *Cecropia pachystachya*, can be introduced later into the system, allowing them to gradually complete their germination cycle as the ecosystem develops and conditions become more suitable.

Species with consistent germination, such as *Senegalia polyphylla*, can be used to manage areas with poor soils or in long-term restoration projects, due to their ability to adapt to different thermal conditions. Species such as *Jacaranda cuspidifolia*, *Copaifera langsdorffii*, *Peltophorum dubium* and *Psidium cattleyanum* maintain high germination even in the face of temperature variations. These characteristics allow them to support local fauna, providing resources such as fruits and shelter, contributing to the ecological balance and resilience of recovering ecosystems.

The performance of species such as *Copaifera langsdorffii*, *Peltophorum dubium*, and *Jacaranda cuspidifolia* at different temperatures suggests potential for their use in areas susceptible to global warming. Using these species can help build plant communities that are more resilient to climate change, ensuring the continuity of forest regeneration in the long term.

Including species with different germination behaviors, such as fast-germinating species (*Mimosa bimucronata*, *Peltophorum dubium*) and slow-germinating species (*Cecropia pachystachya*, *Ceiba speciosa*), favors functional diversity, which is essential for ecological restoration. This approach reduces the risk of dominance of a single species, promoting richer ecological interactions, such as supporting local fauna and improving the microclimate, contributing to the resilience and balance of the recovering ecosystem.

The optimum temperatures for germination vary among species, with some showing superior performance in specific ranges. *Copaifera langsdorffii* maintains high germination rates (84–87.3%) in T1, T2, and T3 conditions, with a significant drop in T4 (13.3%). Similarly, *Jacaranda cuspidifolia* and *Peltophorum dubium* achieve their best results in T1 and T2, with rates above 80%, but show drastic reductions in T4.

On the other hand, species such as *Copaifera langsdorffii*, *Peltophorum dubium*, and *Senegalia polyphylla* demonstrate thermal tolerance and germination plasticity, maintaining high germination rates in a wide range of temperatures (T1, T2, and T3). This characteristic makes these species ideal for restoration projects in regions subject to climatic variations, such as areas with sudden temperature changes or rising averages due to climate change. Their ecological resilience can help stabilize the ecosystem in the initial stages of regeneration.

On the other hand, more sensitive species, such as *C. fissilis*, *C. speciosa*, and M. *fistulifera* which show significant drops in higher temperatures (T3, T4 and T5), are better suited to locations with protected microclimates, such as shaded areas or riparian zones, where thermal conditions are milder and more stable.

In regions with high average temperatures above 40°C, it may be necessary to use more tolerant species, such as *Senegalia polyphylla*, or adopt strategies that reduce heat exposure, such as initial shading.

This study suggests that the origin of the seed collection matrices may influence the species' germination success at different temperatures. Seeds collected from biomes with more arid phytophysiognomies may have more germination success at high temperatures than those from the Atlantic Forest. This difference is likely related to ontogenetic characteristics and the activation of specific genes in response to environmental demands. So, collection by seed ecological zones could be an essential strategy, especially for direct seeding restoration (ROCHA et al., 2020).

Although those results are initial, based only on radicle emergence, it is crucial to consider that this is the first visual step of the germination process. High temperatures of 45ºC (T4) and 50ºC (T5) by 12 hours interfere with the seed radicle development. An increasing temperature could be decisive to the emergence and establishment of this species through direct seeding. That way, it is already possible to observe how rising temperatures influence germination fitness, corroborating with MONDONI et al. (2012) that climate change would indeed change the germination process of seeds.

This work aimed to investigate the germination of tropical forest species. However, the research needs to be expanded into field establishment studies, covering the whole growth cycle and plant survival.

CONCLUSION

From this work alone, it is possible to infer that as temperatures rise, species such as *S. polyphylla*, *C. pachystachya*, and *M. bimucronata* will predominate in the plant strata of restored environments. On the contrary, the ability of these seeds to tolerate desiccation in the germination process was not tested, as the conditions of relative humidity and water availability were not a limiting issue in the experiment. Studies into new seed encapsulation technologies (DUTRA et al., 2023) and global conservation, restoration, and management planning policies guarantee the germination of these species, even in adverse environments.

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