

Enhancing germination of *Sapindus mukorossi* (Gaertn.) through dormancy-breaking treatments

Förderung der Keimung von *Sapindus mukorossi* (Gaertn.) durch Dormanz aufhebende Behandlungen

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Summary

Sapindus mukorossi (Gaertn.), commonly known as soapnut, is a valuable species within the Sapindaceae family, known for its saponin-rich fruits with extensive applications in pharmaceuticals, cosmetics, and natural detergents. However, the hard seed coat of *S. mukorossi* imposes significant dormancy, posing a challenge for propagation. This study evaluates the effectiveness of various pretreatment methods in breaking seed coat dormancy and enhancing germination. The pretreatments included a control (untreated seeds), 15-min hot water soak, 15 min heat at 200 °C, sulfuric acid soak for 1, 2, and 3 h, and mechanical scarification using sandpaper. Over a 30-day period, germination performance was assessed through final germination percentage (FGP), mean germination time (MGT), coefficient of velocity of germination (CVG), time to 50% germination (T50), and mean daily germination (MDG). Results showed that the 2-h sulfuric acid treatment achieved the highest FGP at 96.67%. The control group exhibited a low FGP of 7.50%, indicating high seed dormancy in untreated seeds. Heat treatment and mechanical scarification also improved FGP to 15.83% and 11.67%, respectively. No germination occurred after a hot water soak. Statistical analysis showed significant differences among the treatments for all germination traits (FGP, MGT, CVG, T50, and MDG) with p-values <0.001. This study provides valuable insights into this economically important species' large-scale propagation and cultivation.

Keywords: agroforestry, reforestation, dormancy, germination, sulfuric acid, scarification, *Sapindus mukorossi*

Zusammenfassung

Sapindus mukorossi (Gaertn.), allgemein bekannt als Waschnuss, ist eine wertvolle Art innerhalb der Familie der Sapindaceae, die für ihre saponinreichen Früchte bekannt ist und umfangreiche Anwendungen in der Pharmazie, Kosmetik und in natürlichen Reinigungsmitteln findet. Die harte Samenschale von *S. mukorossi* verursacht jedoch eine bedeutende Dormanz, was die Vermehrung erschwert. Diese Studie bewertet die Wirksamkeit verschiedener Vorbehandlungsmethoden zur Aufhebung der Samenschalen-Dormanz und zur Förderung der Keimung. Die Vorbehandlungen umfassten eine Kontrolle (unbehandelte Samen), 15-minütiges Einweichen in heißem Wasser, 15-minütige Erhitzung bei 200 °C, Einweichen in Schwefelsäure für 1, 2 und 3 Stunden sowie mechanische Skarifikation mit Schleifpapier. Über einen Zeitraum von 30 Tagen wurde die Keimleistung durch den endgültigen Keimungsprozentsatz (FGP), die mittlere Keimzeit (MGT), den Keimgeschwindigkeitskoeffizienten (CVG), die Zeit bis zur 50 % Keimung (T50) und die tägliche mittlere Keimung (MDG) bewertet. Die Ergebnisse zeigten, dass die 2-stündige Schwefelsäurebehandlung die höchste FGP von 96,67 % erreichte. Die Kontrollgruppe zeigte eine niedrige FGP von 7,50 %, was auf eine hohe Samendormanz in unbehandelten Samen hinweist. Hitzebehandlung und mechanische Skarifikation verbesserten ebenfalls die FGP auf 15,83 % bzw. 11,67 %. Nach dem Einweichen in heißem Wasser trat keine Keimung auf. Die statistische Analyse zeigte signifikante Unterschiede zwischen den Behandlungen für alle Keimungseigenschaften (FGP, MGT, CVG, T50 und MDG) mit p-Werten < 0,001. Diese Studie liefert wertvolle Erkenntnisse für die großflächige Vermehrung und Kultivierung dieser wirtschaftlich wichtigen Art.

Schlagwörter: Agroforstwirtschaft, Wiederaufforstung, Dormanz, Keimung, Schwefelsäure, Skarifikation, *Sapindus mukorossi*

1. Introduction

Seed dormancy and germination are fundamental traits to the plant life cycle, influencing both ecological and agricultural systems (Kildisheva et al., 2020; Nautiyal et al., 2023). Physical dormancy, characterized by a hard, impermeable seed coat, is prevalent in 15 angiosperm families, notably within the Fabaceae, Anacardiaceae, and Sapindaceae families (Baskin et al., 2022). This type of dormancy restricts water and gas penetration, preventing the embryo from accessing the necessary conditions for germination (Bhatla and Lal, 2023).

Sapindus mukorossi (Gaertn.), commonly known as soapnut, belongs to the Sapindaceae family and is highly valued for its saponin-rich fruits. These fruits have significant applications in pharmaceuticals, cosmetics, and natural detergents. Traditionally, *S. mukorossi* has been used for its medicinal properties, with its pericarps employed as expectorants and natural surfactants (Upadhyay and Singh, 2012). This species is native to South and Southeast Asia, with significant importance in countries like India, Nepal, Bhutan, and China. It thrives in subtropical and tropical climates and is widely cultivated for its saponin-rich fruits, which are used in traditional medicine, cosmetics, and natural detergents. Indeed, *S. mukorossi* is known for treating various diseases such as excessive salivation, inflammation, epilepsy, chlorosis, migraines, eczema, psoriasis, dental caries, arthritis, common colds, constipation, and nausea (Singh and Sharma, 2019). In Ayurvedic medicine, its seeds are used to remove tan and freckles, cleanse oily skin, and rinse hair due to their rich, natural lather. Moreover, the leaves are used in baths to relieve joint pain, and the roots treat gout and rheumatism (Goyal, 2014).

S. mukorossi is well adapted to a variety of soil types, including loamy and sandy soils, but it prefers slightly acidic to neutral pH conditions. Naturally, it grows in areas with warm temperatures and is known for its resilience in marginal lands, making it suitable for reforestation and agroforestry practices (Sahito et al., 2023). Economically and ecologically, *S. mukorossi* is also important, contributing to various industries and playing a vital role in reforestation and soil conservation programs (Patel and Talathi, 2016). However, its propagation is delayed by a hard seed coat that causes significant dormancy, presenting challenges for germination (Kumar et al., 2024).

Seed dormancy is an essential adaptive trait in many plant species, which prevents germination until conditions are favorable (Klupczyńska and Pawłowski, 2021). In *S. mukorossi*, physical dormancy caused by a hard seed coat restricts water

uptake and gas exchange, delaying or preventing germination (Liu et al., 2024). In natural conditions, the dormancy of soapnut seeds is broken by physical weathering, soil erosion, microbial activity, and temperature fluctuations, which weaken the seed coat and allow water to activate germination. Mechanical abrasion from soil or animals also helps scarify the seed coat. These slow processes lead to delayed and irregular germination, emphasizing the need for pretreatments to enhance and synchronize germination for cultivation. Breaking this dormancy is crucial for enhancing germination rates and ensuring successful seedling establishment. Various methods, including mechanical scarification, chemical treatments, and thermal methods, have been employed to break seed coat dormancy, each with varying degrees of effectiveness. Previous research has highlighted the potential of sulfuric acid in breaking seed dormancy by eroding the seed coat and facilitating water and oxygen uptake, critical for germination. Mechanical scarification, such as sandpaper treatment (SP), is another widely used method that physically abrades the seed coat, enhancing germination speed and uniformity (Rusdy, 2017). However, the comparative efficacy of these methods for *S. mukorossi* has not been thoroughly investigated.

The primary objective of this study is to evaluate the effectiveness of different pretreatment methods, including hot water and sulfuric acid soak, heat, and mechanical scarification, in breaking seed coat dormancy and enhancing germination in *S. mukorossi* seeds. The study aims to assess the impact of these treatments on final germination percentage (FGP), mean germination time (MGT), coefficient of velocity of germination (CVG), time to 50% germination (T_{50}), and mean daily germination (MDG). The results would contribute to the existing body of knowledge on seed dormancy in Sapindaceae and offer insights into optimizing germination protocols for *S. mukorossi*.

2. Material and methods

2.1. Seed harvest and morphometry

In January 2024, mature fruits of *S. mukorossi* were harvested from five trees yielding abundant fruit. The fruits were collected manually. The trees are located in the municipal park of Oran in the northwest of Algeria (35°4'12" N, 0°38'42" W; 111.8 m a.s.l.). Seeds were stored in paper bags under standard laboratory conditions until they were used in March 2024. Seed morphological characteristics of *S. mukorossi* used in this study are presented in Table 1 and Figure 1.

Table 1. Morphometric characteristics of *Sapindus mukorossi* seeds (n = 100)
Tabelle 1. Morphometrische Merkmale von Samen von *Sapindus mukorossi* (n = 100)

Parameters	Mean $\pm$ SD	Minimum	Maximum
Length (cm)	1.38 $\pm$ 0.15	0.97	1.65
Width (cm)	1.28 $\pm$ 0.14	0.99	1.66
Thickness (cm)	1.16 $\pm$ 0.14	0.86	1.37
Weight (g)	1.19 $\pm$ 0.31	0.39	1.69
Coat thickness (cm)	0.17 $\pm$ 0.03	0.11	0.24

SD = standard deviation

The seed sample for this experiment was obtained by mixing all the collected seeds. One thousand seeds weighed 1152.25 ± 15.35 g according to International Seed Testing Association (ISTA) rules (2022). Before the experiment, flotation was used to separate viable from non-viable seeds (Kheloufi, 2017, 2024). According to this technique, around 90% of the seeds recorded as viable.

2.2. Experimental design

Different pretreatments were applied to freshly collected seeds of *S. mukorossi* to break seed coat-imposed dormancy. Each treatment was performed using 120 seeds (four replicates of 30 seeds were used for each pretreatment method). The treatments were 1) control (untreated seeds), 2) soaking seeds in hot water at 80 °C for 15 min, 3) heat treatment by placing the seeds in an oven at 200 °C for 15 min, 4) chemical scarification of intact seeds fully submerged with concentrated sulfuric acid (H_2SO_4 at 98%) for 1, 2, and 3 h, followed by rinsing in tap water for 5 min, and 5) mechanical scarification (abrasion of both sides of the seeds with 40 grit sandpaper).

Seeds from each treatment were germinated in a plastic container between two layers of moist filter paper in total darkness under 25 °C (± 2 °C) for 30 days. According to Haidler et al. (2016), conditions include maintaining adequate moisture, a temperature range of 25–30 °C, and well-drained germination substrates. The seeds were checked for germination daily, and germination was defined as the emergence of radicle from the seed coat (Chovancová et al., 2015). It was essential to maintain a certain level of humidity for the seeds. The filter paper was regularly checked and remoistened with distilled water as needed to prevent drying. A complete randomized design was used to conduct the germination test.

2.3. Germination traits

FGP: FGP represents the total number of seeds germinated out of the total seeds sown in each plastic container. This germination parameter was calculated using the formula:

$$FGP (\%) = \frac{\sum ni}{N} \times 100$$

where FGP is the final germination percentage, ni is the number of germinated seeds on the last day of the test, and N is the total number of seeds incubated per test (Côme, 1970).

MGT: The MGT index shows how fast the seeds emerge in a population. Small MGT value means the seed population has a high rate and vice versa. This was calculated using the following formula:

$$MGT (\text{days}) = \frac{\sum (ti \cdot ni)}{\sum ni}$$

where MGT is the mean germination time, ti is the number of days since the beginning of the test, ni is the number of germinated seeds recorded at time $t(i)$, and $\sum ni$ is the total number of germinated seeds (Orchard, 1977).

T_{50} : T_{50} was developed to find out the time required for 50% seed germination. This is reported through the following formula:

$$T50 (\text{days}) = \frac{ti + (N/2 - ni)(tj - ti)}{(nj - ni)}$$

where N final number of seeds that emerged, nj and ni are the cumulative numbers of seeds that germinated during consecutive counts at tj and ti , when $ni < N/2 < nj$ (Coolbear et al., 1984).

CVG: CVG represents the velocity of germination of seeds in an experiment, which increases with an upsurge in the frequency of germinated seeds. The highest theoretical CVG value is obtained when all sown seeds grow on the first day. This is calculated using the formula:

$$CVG (\%) = \frac{N1 + N2 + N3 \dots Nx}{100} \times N1T1 \dots NxTx$$

in which N is the frequency of seeds germinating every day and T represents the time from sowing to germination of seed N (Khan et al., 2019).

MDG: MDG quantifies how efficiently seeds germinate each day relative to the total number of seeds, providing a standardized measure to compare the germination performance

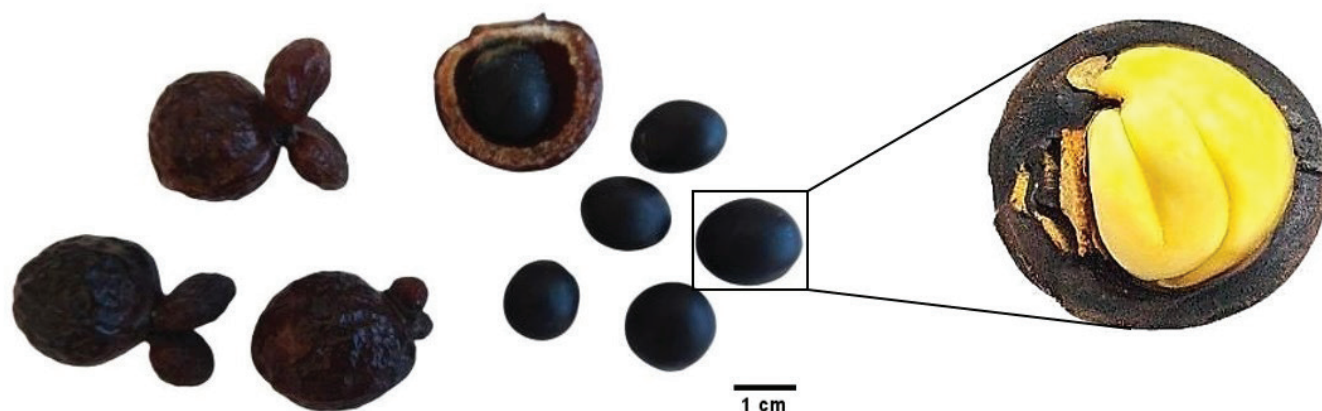


Figure 1. Fruit and seed morphology of *Sapindus mukorossi* (Gaertn.).
Abbildung 1. Frucht- und Samenmorphologie von *Sapindus mukorossi* (Gaertn.).

across different pretreatments. This is reported through the following formula:

$$\text{MDG (\%)} = \frac{\sum Gt}{T} \times 100$$

where Gt is the number of seeds that germinated on day t and T is the total number of days in the germination period (Maguire, 1962).

2.4. Statistical analysis

The effects of different pretreatments on the five variables studied were tested by one-way analysis of variance (ANOVA). Differences between treatments following ANOVA were made by comparison of means. Multiple comparisons of means were carried out using Tukey's test ($p < 0.05$). All statistical analyses were performed using Statistical Analysis System (SAS) software version 9.0 (2002).

3. Results

Statistical analysis showed significant differences among the treatments for all measured traits (FGP, MGT, CVG, T_{50} , and MDG) with p -values < 0.001 , indicating a highly significant effect of the pretreatments on germination (Table 2).

3.1. Final germination percentage

Seeds treated with 2 h of sulfuric acid (2HSA) exhibited the highest FGP at 96.67%, significantly outperforming all other

treatments. Seeds treated with 1 h (1HSA) and 3 h (3HSA) of sulfuric acid also showed substantial improvements in FGP (49.17% and 47.50%, respectively). In contrast, the control group exhibited a low FGP of 7.50%, indicating high seed dormancy in untreated *S. mukorossi* seeds. The hot water treatment for 15 min (15minHW) resulted in no germination (0.00%), demonstrating its ineffectiveness in breaking seed dormancy. SP showed a moderate improvement with an FGP of 11.67%, but this was significantly lower than the sulfuric acid treatments. These results clearly indicate that sulfuric acid treatments, particularly the 2-h soak, are the most effective methods for breaking seed dormancy in *S. mukorossi*.

3.2. Mean germination time

SP produced the shortest MGT at 10.21 days, followed closely by heat treatment for 15 min (15minH200) at 11.95 days. Sulfuric acid treatments showed longer MGTs: 17.01 days for 1HSA, 20.78 days for 2HSA, and 19.99 days for 3HSA. The control group had a significantly longer MGT of 23.92 days, indicating very slow germination. The hot water treatment (15minHW) did not result in any germination, so MGT could not be calculated (NC). These findings suggest that while sulfuric acid treatments significantly increase FGP, they may also extend MGT compared to mechanical or thermal treatments.

3.3. Coefficient of velocity of germination

The seeds treated with SP and seeds that were subjected to heat treatment (15minH200) showed the highest CVG at

Table 2. Effects of different pretreatments on FGP, MGT, T50, CVG, and MDG of *Sapindus mukorossi* for 30 days.

Tabelle 2. Effekte verschiedener Vorbehandlungen auf den endgültigen Keimungsprozentsatz (FGP), die mittlere Keimzeit (MGT), die Zeit bis zur 50 % Keimung (T50), den Keimgeschwindigkeitskoeffizienten (CVG) und die tägliche mittlere Keimung (MDG) von *Sapindus mukorossi* über 30 Tage.

Pretreatments	FGP (%)	MGT (days)	CVG (%)	T ₅₀ (days)	MDG (%)
Control	7.50 ± 3.19 ^d	23.92 ± 2.20 ^a	4.21 ± 0.37 ^d	22.38 ± 3.27 ^a	0.25 ± 0.11 ^d
15minHW	0.00 ^c	NC	0.00 ^c	NC	0.00 ^c
15minH200	15.83 ± 3.19 ^c	11.95 ± 0.58 ^d	8.38 ± 0.39 ^b	11.42 ± 1.19 ^{bc}	0.53 ± 0.11 ^c
1HSA	49.17 ± 5.00 ^b	17.01 ± 0.96 ^c	5.89 ± 0.34 ^c	14.91 ± 1.08 ^b	1.64 ± 0.17 ^b
2HSA	96.67 ± 3.85 ^a	20.78 ± 1.04 ^b	4.82 ± 0.23 ^{cd}	20.43 ± 0.23 ^a	3.22 ± 0.13 ^a
3HSA	47.50 ± 3.19 ^b	19.99 ± 0.52 ^b	5.00 ± 0.13 ^{cd}	19.25 ± 0.68 ^a	1.58 ± 0.11 ^b
SP	11.67 ± 1.92 ^{cd}	10.21 ± 1.18 ^d	9.89 ± 1.11 ^a	9.00 ± 1.00 ^c	0.39 ± 0.06 ^{cd}
F-value	441.82	210.49	165.29	105.59	441.83
p-value	<0.001	<0.001	<0.001	<0.001	<0.001

The different letters in the same column indicate a significant difference at $p < 0.05$, as evaluated by Tukey's test

NC = not calculated; Control = untreated seeds; 15minHW = 15 min soaking in hot water; 15minH200 = 15 min heat at 200 °C; 1HSA = 1 h soaking in sulfuric acid; 2HSA = 2 h soaking in sulfuric acid; 3HSA = 3 h soaking in sulfuric acid; SP = sand paper; FGP = final germination percentage; MGT = mean germination time; T₅₀ = time to 50% germination; CVG = coefficient of velocity of germination; MDG = mean daily germination

9.89% and 8.83%, respectively, indicating a faster germination rate. Sulfuric acid treatments showed lower CVGs: 5.89% for 1HSA, 4.94% for 2HSA, and 5.04% for 3HSA, suggesting a slower germination rate. The control group had a CVG of 4.21%, while hot water treatment (15minHW) showed no germination (0.00%). A high CVG is generally desirable as it indicates rapid germination, which is crucial for certain agricultural applications. Thus, the mechanical treatment with SP appears to be the most effective in improving the germination rate.

3.4. Time to 50% of germination

The T50 values revealed significant differences among the pretreatments. The control group exhibited a high T50 of 22.38 days, indicating slow germination due to the strong dormancy imposed by the hard seed coat. The 15minH200 treatment reduced T50 to 11.42, demonstrating its effectiveness in accelerating germination by partially weakening the seed coat. The 1HSA treatment also decreased T50 to 14.91 days, reflecting moderate success in enhancing germination speed. Conversely, the 2HSA and 3HSA treatments had T50 values of 20.43 and 19.25 days, respectively, which, despite achieving high FGPs, showed slower progress toward reaching 50% germination. For the 15minHW treatment, germination did not occur and T₅₀ was not calculated, indicating the ineffectiveness of this method in breaking dormancy.

3.5. Mean daily germination

The MDG values showed significant differences in the germination rates across the pretreatment methods. The control group had a low MDG of 0.25. The 15minHW treatment resulted in no germination, indicating that hot water treatment was ineffective in stimulating seed germination. The 15minH200 treatment showed a slight increase in MDG of 0.53. The 1HSA treatment showed a marked improvement, with an MDG of 1.64, indicating a faster rate of germination compared to the control. The 2HSA treatment achieved the highest MDG of 3.22, demonstrating the most significant increase in germination speed, as the seeds rapidly reached 50% germination. The 3HSA treatment had an MDG of 1.58, which was slightly lower than the 2-h acid treatment but still an improvement over the control. The SP treatment had an MDG of 0.39, showing a minor improvement over the control.

Figure 2 illustrates the progressive development of *S. mukorossi* seedlings over successive weeks from the initial stage of germination (treated by 2-h sulfuric acid). Starting from the right, the early stages show the emergence of the radicle and the beginning of seedling growth. As the weeks progress toward the left, the seedlings exhibit significant growth with the development of primary leaves and elongation of the stem and root systems. The increasing complexity and robustness of the plants highlight the effective germination and subsequent growth phases, demonstrating the successful breaking of seed coat dormancy and the establishment of healthy seedlings. The scale bar indicates a length of 1 cm, providing a reference for the growth stages.



Figure 2. Developmental stages of *Sapindus mukorossi* from germination (weekly progression).
Abbildung 2. Entwicklungsstadien von *Sapindus mukorossi* von der Keimung an (wöchentlicher Fortschritt).

4. Discussion

This study aimed to evaluate the effectiveness of various pre-treatment methods in breaking seed dormancy and enhancing germination in *S. mukorossi*. The results clearly demonstrate that sulfuric acid treatments, particularly the 2-h soak, significantly improved the germination performance of *S. mukorossi* seeds across multiple parameters and resulted in the highest FGP of 96.67%. This finding aligns with previous research indicating that sulfuric acid effectively breaks seed coat dormancy by eroding the seed coat, thereby enhancing water and oxygen uptake, which are critical for germination (Baskin & Baskin 2020). The significant improvement in FGP with 2HSA highlights the effectiveness of chemical scarification in breaking the physical dormancy of *S. mukorossi* seeds by dissolving the hard seed coat and allowing water to start germination. The time-dependent nature of SA is evident, as the 3-h treatment resulted in a lower FGP (47.5%), possibly due to overexposure causing seed damage. These results are consistent with other studies on Fabaceae species. Kheloufi (2022) showed similar im-

provements in germination with sulfuric acid treatments. In addition, Baskin and Baskin (1998) noted that sulfuric acid is a commonly used method to overcome physical dormancy in seeds with hard seed coats. Kheloufi et al. (2018) reported that treating seeds with sulfuric acid removed some or all of the cuticular layer, resulting in rapid germination.

MGT was significantly reduced in SP treated seeds to 10.21 days, compared to 23.92 days in the control. Although the sulfuric acid treatments (1HSA, 2HSA, 3HSA) also reduced MGT, they did so to a lesser extent (17.01–20.78 days). While sulfuric acid treatments are effective in enhancing germination percentage, they may induce some degree of seed coat damage that prolongs the germination process. This is a common observation in seeds with hard coats, where chemical treatments may create multiple microfractures, leading to a more prolonged germination period (Nikolaeva et al., 1985; Vinodkumars et al., 2014).

CVG was highest in the seeds treated with SP (9.89%), indicating a faster and more uniform germination process. Sulfuric acid treatments, while effective in breaking dormancy, resulted in lower CVG values (4.94%–5.89%). The mechan-

ical scarification provides a more consistent and rapid germination response, likely due to the more uniform abrasion of the seed coat compared to the chemical erosion by sulfuric acid (Wang et al., 2011).

T_{50} was significantly reduced in SP treatment to 9.00 days, compared to 22.38 days in the control. The sulfuric acid treatments also showed substantial reductions in T_{50} (9.40–9.46 days), indicating their effectiveness in accelerating the germination process. However, the slight delay compared to SP treatment indicates that while chemical treatments are highly effective, they may also introduce variability in the speed of germination due to differing levels of seed coat erosion (Copeland and McDonald, 2012).

MDG was highest in 2HSA treatment (3.31%), reflecting a consistent and high daily germination rate. This highlights the potential of sulfuric acid treatments to enhance not only the overall germination percentage, but also the daily emergence rate, which is crucial for establishing uniform seedling stands in field conditions (Bewley et al., 2013).

The findings of this study have significant implications for the large-scale propagation of *S. mukorossi*. The high FGP and MDG observed with the 2HSA treatment suggest that sulfuric acid scarification can be an effective method for ensuring high germination rates and uniform seedling establishment. However, the extended MGT and lower CVG compared to mechanical scarification indicate that a balance must be struck between achieving high germination percentages and ensuring rapid and uniform germination. For practical applications, a combination of treatments or optimization of exposure times may be necessary to maximize the benefits of each method (ISTA, 2022).

Comparing the heat and hot water treatments, it is evident that the 15-min heat treatment at 200 °C was significantly more effective than the hot water treatment. The substantial increase in germination traits with 15minH200 indicates that higher temperature treatments are more effective in overcoming physical dormancy in *S. mukorossi* seeds. According to Haider et al. (2016), the seed soaking in hot water for 10 sec showed the highest germination (72%) and it occurred between 34 and 78 days after sowing. Seed size, ecotype, and pre-sowing treatments often control the germination and initial seedling growth in many tree species (Kheloufi et al., 2019; Mansouri et al., 2024). Thermal scarification through high-temperature treatments, such as exposure to dry heat, is known to be effective for species with hard seed coats. Studies on various *Acacia* species have shown that dry heat treatments can significantly enhance germination rates by mimicking the natural effects of wildfires, which are common in

the natural habitats of these species (Baskin et al., 2000). The use of dry heat treatments is particularly effective for seeds that are adapted to fire-prone environments, where the intense heat helps to break seed dormancy (Moro et al., 2021). The strength of the seed coat helps in the preservation and conservation of the seeds against mechanical damage, facilitating their survival in arid soils during droughts or enabling natural dispersion and recolonization following fire events (Shiferaw et al., 2018; Dalling et al., 2020).

The hard seed coat helps the seeds against mechanical damage to survive in the soil during drought or allows natural dispersal and recolonization after fire (Khurana and Singh, 2001). The seed surface morphology revealed that a hard and impermeable testa is the primary barrier to imbibition, consequently delaying germination (Lamont and Pausas, 2023). Our study demonstrated the efficiency of different pretreatments in overcoming seed dormancy and enhancing germination. These findings are consistent with general observations in the Fabaceae, Sapindaceae, and Anacardiaceae families, where physical and chemical scarification are commonly used to enhance germination (Cook et al., 2008; Kheloufi, 2022, 2024; Baskin and Baskin, 2022). Pretreatments such as soaking in sulfuric acid, mechanical scarification, and soaking in hydrogen peroxide have shown varying degrees of success in breaking seed coat dormancy and promoting germination (Nautiyal et al., 2023).

The development of a very hard seed coat in its fully desiccated state is typically attributed to the substantial presence of heavily thickened galactomannan or mannan polymers lining the endosperm cell walls (Steinbrecher and Leubner-Metzger, 2017). Within the endosperm, the presence of hydrophilic galactomannan leads to a mucilaginous transformation upon imbibition and subsequent hydrolysis (Zandi et al., 2015). While impermeability of the seed coat and its mechanisms for delaying germination are common traits among legumes, they serve to delay seed germination under adverse environmental conditions (Naik and Deshpande, 2021).

Future research should explore the underlying mechanisms of dormancy breaking by sulfuric acid in *S. mukorossi* seeds. Investigations into the optimal concentration and duration of sulfuric acid treatment, as well as the potential effects on seedling vigor and subsequent growth stages, would provide valuable insights. Furthermore, the application of integrated pretreatment strategies, combining mechanical and chemical methods, could be evaluated to further enhance germination performance and reduce variability (Araújo et al., 2016).

5. Conclusion

This study demonstrates that sulfuric acid treatments, particularly a 2-h soak, are highly effective in breaking seed coat dormancy and enhancing germination in *S. mukorossi*. The significant improvements in FGP, MDG, and reduced T_{50} highlight the potential of chemical scarification for large-scale propagation improvement. Mechanical scarification with SP and heat treatment also showed potential, particularly in reducing MGT and increasing CVG. The results of this study have significant implications for agricultural practice, particularly in enhancing the cultivation and propagation of *S. mukorossi*. By adopting this pretreatment method, farmers and nurseries can reduce the germination time and increase seedling production efficiency, ensuring uniform and synchronized plant growth. In field applications, these results can guide seed preparation protocols for reforestation projects, agroforestry systems, or commercial plantations.

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