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Improving germination and early seedling growth of marula (*Sclerocarya birrea* (A.Rich.) Hochst.) through hydro-priming

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Introduction: Despite the socio-economic and nutritional significance of marula (*Sclerocarya birrea* (A.Rich.) Hochst.) in sub-Saharan Africa, its domestication and commercial cultivation are constrained by poor seed germination due to a hard, impermeable seed coat. This study aimed to determine the most effective hydro-priming duration for enhancing germination and early seedling growth of marula under controlled and field conditions.

Methods: Separate pot (laboratory) and field experiments were conducted using a completely randomised design (CRD) with four replications. Mature marula seeds were subjected to four hydro-priming durations: no soaking (control), soaking for 24 h, 48 h, or 60 h in distilled water. Data were collected on germination percentage, germination index, seedling height, root length, number of secondary roots, and vigour index. Two-way analysis of variance (ANOVA) was performed, and means were separated using Fisher's protected least significant difference (LSD) test at $p < 0.05$.

Results: Hydro-priming duration had a highly significant ($p < 0.001$) effect on germination percentage in both experiments. In the pot experiment, the highest germination (45%) was achieved after 70 days with 48 h of priming, while in the field experiment, 60 h of priming produced the highest germination (77.5%) after 45 days. Germination index and root length were also significantly ($p < 0.05$) affected by priming duration. The longest roots were recorded from seeds primed for 60 h in both the pot (9.46 cm) and field (16 cm) experiments. Significant method $\times$ treatment interactions ($p < 0.01$) were observed for final germination, secondary root number, germination index, and vigour index, indicating environment-specific optimal priming durations.

Discussion: Extended hydro-priming (48–60 h) consistently enhanced metabolic activation, resource mobilisation, and subsequent seedling vigour, particularly under field conditions. The superior performance of field-sown seeds was attributed to both the longer storage duration (15 months) and favourable summer growing conditions. The contrasting proliferation of secondary roots under pot conditions suggests a phenotypic adaptive response to resource limitation. It is concluded that hydro-priming is an effective, low-cost technique to improve marula seed germination and early seedling establishment. For direct field seeding, a 60-h hydro-priming treatment is

recommended, whereas 48 h is optimal for containerised nursery production. Planting during the summer months (October–November) is advised to maximise germination potential.

KEYWORDS

germination, growth, hydro-priming, marula, root growth, seed dormancy

1 Introduction

The use of seeds as propagules is considered the easiest, cheapest, and most common means for many agroforestry and timber tree species (Akinnifesi et al., 2007). This is because seeds are easy to handle and are relatively easy to produce (Black, 1989). Seeds are also used to raise rootstocks in other propagating techniques such as grafting, air-layering, and budding (Hartmann et al., 2002). Seed germination and early growth and development are important stages in indigenous fruit tree species (Hossain et al., 2005). However, there has been very little research on seed germination and seed storage methods for many of Zimbabwe's indigenous fruit tree species. Seeds of some indigenous fruit tree species, such as marula, are characterized by a hard seed coat that is impermeable to water and thus hinders germination of the seeds (Dhupper, 2013).

Marula is a member of Anacardiaceae family (Masarirambi and Nxumalo, 2012; Mng'omba et al., 2012). It is one of the ten most used indigenous fruit tree species in sub-Saharan Africa (Muok et al., 2011). It occurs in the arid and semi-arid parts of Africa, is common in coastal regions, and is also found in high altitudes up to 1,600 m above sea level (Muok et al., 2011). Marula contributes significantly to the income generated by the region's inhabitants (Muok et al., 2011). Many inhabitants utilize the leaves, fruits, stem bark, and roots of this tree in these regions for food, medicine, and timber. The fruit pulp of marula is an important source of vitamin C (Dlamini, 2011). The nuts inside the hard outer covering of the seed are also a rich source of nutrients like protein, oil, magnesium, phosphorous, and potassium (Muok et al., 2011). The fruit is processed at a small scale to produce wines, drinks, and oil, among other products (Nwonwu, 2006; Shackleton et al., 2008). The multi-purpose nature of the marula fruit tree and its significance in the African landscape has resulted in the species being associated with many religious beliefs and ceremonies across Africa (Leakey and Tchoundjeu, 2001).

Because of this background of economic importance, marula has been identified as a high potential indigenous fruit tree species for crop development and improvement in Southern Africa (Mollel and Goyvaerts, 2004). This focus on the species has raised concerns about the pressure the demand for marula products will exert on the existing marula populations and the sustainability of industrial-scale commercialization of marula products relying on currently available wild stands which are rapidly deteriorating due to deforestation and the clearing up of land for human settlement and agriculture (Nwonwu, 2006). Therefore, it is against this background that the understanding of reproductive biology and the factors influencing the germination of marula become pivotal.

Previous studies have shown that marula seeds do not germinate readily when dropped from the canopy, but may remain quiescent for up to 6 months in a transient seed bank in the soil (Shone, 1979; Von Teichman et al., 1986). These seeds

usually germinate after sufficient rainfall in the following season or two (Helm et al., 2011). Under natural conditions, factors like light, water, temperature, oxygen and mechanical pressures have been observed to improve seed germination in species like marula (Moyo et al., 2009). The mechanical dormancy has also been broken through prior seed treatments like ingestion by mammals which passes the seed through the acidic digestive system or by manual removal of the opercula which is the outer covering of the seeds (Von Teichman et al., 1986). Soaking seeds with the appropriate concentration of pre-sowing treatment before planting has been used to weaken the seed coat and leach away the germination inhibitors (Raheem et al., 2014; Alhindaassi et al., 2025). Furthermore, when seeds are soaked in water before sowing, seedling development is also enhanced by modulating pre-germination metabolic activity before the emergence of the radicle, which generally enhances germination rate and plant performance (Mondal and Bose, 2022). This study aimed to determine the most effective hydro-priming duration that promotes the germination and initial growth of marula seeds.

2 Materials and methods

2.1 Site description

The winter research experiment was carried out in a laboratory and the summer experiment in an open field at Midlands State University, Main campus Gweru (Fig 4.1). Midlands State University is classified under Natural Region III of Zimbabwe's Agro-ecological zones (Manatsa et al., 2020), and is located in the coordinates 19.48° S and 19.48° W and has an altitude of 1,425 m above sea level. The average annual rainfall ranges from 600 mm to 750 mm, and the mean temperature is around 20 °C–25 °C.

2.2 Seed collection and processing

Freshly ripened fruits were collected from beneath a tree domesticated in a farmer's agricultural field in the Chivi district of Zimbabwe at 20° 24'S, and 30° 13'E in May 2020. The tree has been retained on the farm for its big fruits with high juice content. The fruits were brought to the laboratory at the Midlands State University where they were peeled and pulp was removed from the seeds. The seeds were washed, dried, and then stored at room temperature until setting up the trials. Before germination, the viability of the seeds was determined using the dens metric test with tap water to remove the nonviable seed. A total of 160 healthy seeds with no visible defects were used for each experiment. The seeds were divided into 4 seed lots of 40 seeds. Each seed lot was placed in a separate bucket with distilled water. Soaking was staggered to ensure that the different seed lots would have been soaked for 24, 48, and 60 h respectively. After soaking for the

TABLE 1 Effects of hydro-priming duration on final germination percentage.

Method	Treatment			
	0 h	24 h	48 h	60 h
Pot	20.0 ^a	17.5 ^a	45.0 ^{bc}	40.0 ^b
Field	42.5 ^b	55.0 ^{cd}	60.5 ^d	77.5 ^e
Mean	44.7			
P-value	0.08			
LSD _{0.05}	10.35			
CV%	15.8			

The symbols denote differences in statistical significance between treatment means. Values with a different symbol e.g. a and b are statistically different whereas values with the same symbol are statistically similar meaning that there is no significant difference between the treatment means.

TABLE 2 Effects of hydro-priming duration on vigor index.

Method	Treatment			
	0 h	24 h	48 h	60 h
Pot	0.05 ^a	0.03 ^a	0.09 ^a	0.09 ^a
Field	19.43 ^b	27.14 ^c	31.05 ^d	42.86 ^e
Mean	15.09			
P-value	<0.001			
LSD _{0.05}	3.406			
CV%	15.3			

The symbols denote differences in statistical significance between treatment means. Values with a different symbol e.g. a and b are statistically different whereas values with the same symbol are statistically similar meaning that there is no significant difference between the treatment means.

different durations, soaking water was discarded, and seeds were allowed to dry in the air for 1 hour before planting.

2.3 Treatments and experimental design

The different hydro-priming durations formed the treatments. Treatment 1 consisted of unsoaked seeds, T2- 24 h hydro-priming duration, T3- 48 h hydro-priming duration, T4- 60 h hydro-priming duration. Seven-liter plastic bucket pots were arranged in a CRD replicated four times in the laboratory experiment. Ten seeds were sown in each pot which represented a single experimental plot. The seeds were planted in a medium of topsoil, collected around the campus forest area, at a depth of 5 cm. All the plastic pots were perforated at the bottom to allow free drainage. The pots were watered every 2 days to maintain the soil at field capacity, and the pots were exposed to sunlight for 10 h every day and kept in the laboratory overnight to avoid the effects of night frost. In the field experiment, a trench 2 m in length by 1-m width by 20 cm in depth was dug and lined with polythene plastic. The trench was then filled with a medium composed of forest topsoil. Seeds of marula were then planted in the medium using a spacing of 5 cm in-row and 10 cm inter-row at a depth of

TABLE 3 Effects of hydro-priming duration on seedling height.

Method	Seedling height	Root length
Pot	29.02 ^a	7.08 ^a
Field	36.12 ^b	14.43 ^b
Treatment		
0 h	28.10 ^a	8.45 ^a
24 h	32.90 ^b	11.23 ^b
48 h	33.26 ^b	10.59 ^{ab}
60 h	36.02 ^b	12.73 ^b
Mean	32.57	10.75
P-value	<0.01	<0.01
LSD _{0.05}	4.534	2.167
CV%	9.5	13.7

The symbols denote differences in statistical significance between treatment means. Values with a different symbol e.g. a and b are statistically different whereas values with the same symbol are statistically similar meaning that there is no significant difference between the treatment means.

5 cm and covered with the same medium. Ten seeds were planted in each row, representing a single experimental plot, and each plot representing each treatment was replicated four times. A two-factor randomized complete block design with four replications (blocks) was employed to evaluate the effects of method (two levels: field and pot) and treatment (four levels: exposure durations: 0, 24, 48, and 60 h) on seven germination and seedling growth parameters in a plant species. A total of 32 experimental units were assessed. Data were analyzed using two-way analysis of variance (ANOVA) with orthogonal factorial structure, followed by Fisher's protected least significant difference (LSD) tests for mean comparisons where applicable.

2.4 Data collection

Data were collected on the following parameters:
Germination parameters.

The germination of marula seeds was observed and recorded daily and the germination trial was stopped when there was no seed germination observed for a sustained period of 21 days (Eyog-Matig et al., 2007). Seeds were considered to have germinated when there was a visible protrusion of a split seed coat with the cotyledons, hypocotyls, and epicotyl above the soil's surface. Weekly germinated seeds were observed and counted. The germination percentage was calculated using the formula below:

$$\text{Germination Percentage} = \frac{\text{Number of seeds germinated}}{\text{Total number of seeds sown}} \times 100$$

At the end of the germination experiment, we calculated the germination index (GI) as described by:

$$\text{Germination Index} = \frac{\text{Number of germinated seeds}}{\text{Days to the first count}} + \frac{\text{Number of germinated seeds}}{\text{Days to the last count}}$$

TABLE 4 Effects of hydro-priming duration on the number of secondary roots.

Method	Treatment			
	0 h	24 h	48 h	60 h
Pot	11.25 ^a	23.00 ^c	19.75 ^{cde}	21.75 ^{de}
Field	17.00 ^{abcd}	16.25 ^{abc}	13.25 ^{ab}	12.25 ^{ab}
Mean	16.81			
P-value	<0.01			
LSD _{0.05}	4.881			
CV%	19.7			

The symbols denote differences in statistical significance between treatment means. Values with a different symbol e.g. a and b are statistically different whereas values with the same symbol are statistically similar meaning that there is no significant difference between the treatment means.

TABLE 5 Effects of hydro-priming duration on germination index.

Method	Treatment			
	0 h	24 h	48 h	60 h
Field	5.85 ^b	6.62 ^b	16.18 ^c	16.98 ^c
Pot	0.11 ^a	0.21 ^a	0.15 ^a	0.18 ^a
Mean	5.78			
P-value	<0.001			
LSD _{0.05}	3.838			
CV%	45.1			

The symbols denote differences in statistical significance between treatment means. Values with a different symbol e.g. a and b are statistically different whereas values with the same symbol are statistically similar meaning that there is no significant difference between the treatment means.

Data on seedling growth performance was collected 90 days after planting. Three seedlings were randomly selected in each plot, and plant height was measured using a string and ruler to the nearest cm from just below the cotyledons. Three plants in each experimental unit were uprooted, and the length of the roots was measured using a string and ruler. The number of secondary roots was counted and recorded. The vigor index was calculated as final germination $\times$ total plant length.

2.5 Data analysis

A two-factor randomized complete block design with four replications (blocks) was employed to evaluate the effects of method (two levels: field and pot) and treatment (four levels: exposure durations: 0, 24, 48, and 60 h) on seven germination and seedling growth parameters in a plant species. A total of 32 experimental units were assessed. Data were analyzed using two-way analysis of variance (ANOVA) with orthogonal factorial structure, followed by Fisher's protected least significant difference (LSD) tests for mean comparisons where applicable.

3 Results

3.1 Effects of hydro-priming duration on final germination percentage

The ANOVA revealed significant main effects of method ($F_{1,21} = 127.70$, $p < 0.001$) and treatment ($F_{3,21} = 27.47$, $p < 0.001$), as well as a significant method $\times$ treatment interaction ($F_{3,21} = 5.11$, $p = 0.008$). The grand mean final germination was 44.7% (Table 1).

The field method produced substantially higher germination (58.8%) compared to the pot method (30.6%). Across treatments, germination increased progressively with exposure duration: 0 h (31.3%), 24 h (36.3%), 48 h (52.5%), and 60 h (58.8%). The interaction effect indicated that the response to treatment duration differed between methods. Under pot conditions, germination increased from 20.0% (0 h) to 45.0% (48 h), with a slight decline to 40.0% at 60 h. Under field conditions, germination showed a monotonic increase from 42.5% (0 h) to 77.5% (60 h). The residual coefficient of variation (CV) was 15.8%, indicating acceptable experimental precision.

3.2 Effects of hydro-priming on vigor index

Highly significant effects were detected for method ($F_{1,21} = 1,347.02$, $p < 0.001$), treatment ($F_{3,21} = 35.74$, $p < 0.001$), and their interaction ($F_{3,21} = 35.46$, $p < 0.001$) (Table 2). The grand mean germination index was 15.09. Field conditions yielded an exceptionally high index (30.12) compared to pot conditions (0.06). Treatment effects under pot conditions showed progressive increases: 19.43 (0 h), 27.14 (24 h), 31.05 (48 h), and 42.86 (60 h). In contrast, pot conditions produced near-zero values across all treatments (0.05–0.09). Residual CV was 15.3%.

3.3 Effects of hydro-priming duration on seedling height

Both method ($F_{1,21} = 42.49$, $p < 0.001$) and treatment ($F_{3,21} = 9.12$, $p < 0.001$) exerted significant main effects on seedling height, whereas the interaction was non-significant ($F_{3,21} = 0.83$, $p = 0.494$). The grand mean height was 32.57 cm. Field-grown seedlings attained greater height (36.12 cm) than pot-grown counterparts (29.02 cm) (Table 3). Height increased with treatment duration: 28.10 cm (0 h), 32.90 cm (24 h), 33.26 cm (48 h), and 36.02 cm (60 h). The residual CV was 9.5%, indicating high precision.

3.4 Effects of hydro-priming duration on root length

Highly significant main effects of method ($F_{1,21} = 199.03$, $p < 0.001$) and treatment ($F_{3,21} = 11.63$, $p < 0.001$) were observed for root length. The interaction approached but did not reach significance ($F_{3,21} = 2.46$, $p = 0.091$). Grand mean root length was 10.75 cm. Field conditions produced markedly longer roots (14.43 cm) compared to pot conditions (7.08 cm). Root length

increased with treatment duration: 8.45 cm (0 h), 11.23 cm (24 h), 10.59 cm (48 h), and 12.73 cm (60 h). Residual CV was 13.7%.

3.5 Effects of hydro-priming duration on the number of secondary roots

Analysis of secondary root number revealed significant main effects of method ($F_{1,21} = 13.12$, $p = 0.002$) and treatment ($F_{3,21} = 3.69$, $p = 0.028$), along with a highly significant interaction ($F_{3,21} = 8.40$, $p < 0.001$). The grand mean was 16.81 secondary roots. Contrary to other parameters, pot conditions produced more secondary roots (18.94) than field conditions (14.69). Treatment effects were non-monotonic: 14.12 (0 h), 19.62 (24 h), 16.50 (48 h), and 17.00 (60 h) (Table 4). The interaction arose because under pot conditions, secondary roots peaked at 24 h (23.00) and remained elevated (19.75 at 48 h, 21.75 at 60 h), whereas under field conditions, secondary roots declined progressively from 17.00 (0 h) to 12.25 (60 h). Residual CV was 19.7%.

3.6 Effects of hydro-priming duration on vigor index

All effects were highly significant: method ($F_{1,21} = 148.48$, $p < 0.001$), treatment ($F_{3,21} = 10.56$, $p < 0.001$), and interaction ($F_{3,21} = 10.52$, $p < 0.001$) (Table 5). The grand mean vigor index was 5.78. Field conditions produced a markedly higher vigor index (11.41) than pot conditions (0.16). Under field conditions, vigor index increased with treatment duration: 5.85 (0 h), 6.62 (24 h), 16.18 (48 h), and 16.98 (60 h). Under pot conditions, vigor index remained near zero across all treatments (0.11–0.21). Residual CV was 45.1%, indicating substantial variability.

4 Discussion

4.1 Effects of hydro-priming duration on germination parameters

The pot study showed the Marula seeds' low germination potential, with the highest final germination rate being in seeds soaked for 48 h (45%). This study corroborates previous studies that have shown that the most efficient hydro-priming durations are 24 and 48 h, and a germination rate of 49% has been reported in *Sclerocarya birrea* seeds soaked for 48 h (Hamidou et al., 2014). A higher coefficient velocity of emergence has also been observed in seeds of *Maesobotrya barteri* subjected to hydro-priming before planting (Peter-Onoh et al., 2014), as is the case in this study. Longer durations of hydro-priming have been seen to result in higher cumulative germination in wild sunflowers, and improve the rate of growth in seedlings, and this is evident in the results of this study as the seeds soaked for 60 h produced seedlings with the highest average seedling height and root length (Akinola et al., 2000; Abdulrahmani et al., 2007). However, the current findings do not conform to earlier reports by Joker and Erdey, 2003, who reported 70% germination rates 1 week after sowing and 85% a week after. One interesting and related observation made in this study was

that the germination rate suddenly increased in all the treatments when the same seed was used in the field experiment. The field experiment was carried out 15 months after seed preparation compared to 2 months when the laboratory pot experiment was carried out. This explains another theory related to the storage duration of seed after harvest. Seeds stored for a prolonged time have exhibited a higher germination rate than those stored for shorter durations before sowing (Gamene et al., 2005; Muok et al., 2007). This is because seed storage leads to reserve carbohydrate accumulation, providing the seed and emerging plant with energy requirements. This could explain the relatively higher germination rates in the field experiment across all treatments, as the seeds had been stored longer than in the pot experiment.

Secondly, the slow germination and resultant lower germination index in the pot experiment are probably attributed to the time of the year the trial was planted. Marula seeds have been observed to grow best in the summer months of October and November when conditions are hot and wet *in situ*, contributing to the permeability of seeds to water to break dormancy (Shone, 1979; Goosen et al., 1985; Mateke, 1996; Baskin et al., 2000). This again helps explain the difference in results between the pot and field experiments. The low germination rates in the pot experiment may be due to a slow rate of water uptake by the seeds across all the treatments. The observation was also made in seeds of *Elaeocarpus* spp. (Khan et al., 2003; Bhuyan et al., 2004). The low germination percentage may also be attributed to the duration of seed storage, as long periods of storage between 1 and 2 years have been observed to enhance germination (Muok et al., 2011). This also helps explain the significant improvement in germination percentages and germination index across all treatments in the field experiment planted in the summer of the following year after the pot experiment.

4.2 Effects of hydro-priming duration on growth parameters

Seeds subjected to the different hydro-priming durations had higher plant heights than seeds that were sown without the pretreatment. This is because the process of photosynthesis is triggered quicker in soaked seeds than in the seeds with no soaking (Missanjo et al., 2014). Similar results have been reported in *Elaeocarpus serratus* L. (Doody and O'Reilly, 2008; Amoakoh et al., 2017). These findings are also in line with the findings of Hossain et al. (2013) who argued that seed pre-treatments influenced growth parameters like shoot length and root length before planting. Seedlings of marula have been observed to have excellent initial growth and development, with seedlings growing up to 50 cm within 60 days after planting (Hamidou et al., 2014). The relatively low plant heights and root lengths across all treatments in the pot experiment can be attributed to the time of the year the trial was carried out, an observation supported by a study carried out in the winter months in the Western Cape of South Africa (Ehrich et al., 2010). In this study, the root length had an inverse relationship with the number of secondary roots. The contrasting pattern observed for secondary root number, greater under pot

conditions, suggests a morphogenetic response to environmental stress. Plants grown under conditions with limited nutrient resources may allocate proportionally more resources to lateral root proliferation as an adaptive foraging strategy to compensate for reduced resource availability. This phenomenon is consistent with the concept of phenotypic plasticity, wherein root system architecture adjusts to optimize nutrient and water acquisition under limiting conditions.

Exposure duration significantly influenced most parameters, with longer durations (48–60 h) generally promoting superior performance. This pattern is consistent with a priming or preconditioning effect, wherein controlled hydration prior to germination activates metabolic processes including DNA repair, antioxidant enzyme systems, and reserve mobilization, thereby enhancing subsequent germination and early seedling growth.

The monotonic increase in pot-based germination index from 5.85 (0 h) to 16.98 (60 h) represents a significant enhancement, suggesting that extended priming durations are particularly beneficial under optimal growing conditions. Conversely, the non-significant treatment effect on survival rate indicates that once germination occurs, subsequent survival is primarily determined by environmental conditions (method) rather than pre-treatment duration.

The non-monotonic response of secondary root number to treatment duration, peaking at 24 h then declining, suggests a hormetic response. Moderate priming durations may stimulate lateral root initiation, whereas extended exposure may exhaust carbohydrate reserves or induce secondary dormancy mechanisms that suppress root branching.

Hydro-priming seeds before planting has a significant effect on the vigor index, a measure of seedling establishment. In this study, seeds soaked for 60 h before planting had the highest vigor index in the pot and field experiments. These findings conform to [Harris et al. \(2001\)](#), who found that hydro-priming promoted establishment and early growth resulting in early maturity and faster development. [Hossain et al. \(2005\)](#) also reiterate these findings stating that higher values of the vigor index are found when seeds are soaked for 48 h or longer.

4.3 Interaction effects

Significant method $\times$ treatment interactions were observed for final germination, secondary root number, germination index, and vigor index. These interactions indicate that the optimal priming duration differs between growing environments. For pot conditions, 48 h maximized germination and vigor index, whereas under field conditions, the 60-h treatment consistently produced the highest values across most parameters. This differential response has practical implications: recommendations for seed priming protocols should be environment-specific.

4.4 Biological and agronomic implications

From a physiological perspective, the results demonstrate that seed priming duration interacts with post-germination growing conditions to modulate multiple facets of seedling establishment.

The enhancement of root length (51% increase from 0 to 60 h under field conditions) and shoot height (28% increase) by extended priming indicates improved resource mobilization and cell elongation capacity.

Agronomically, the findings suggest that for pot-based production systems (e.g., containerized nursery stock, greenhouse cultivation), a 48-h priming treatment maximizes germination speed, uniformity, and early growth. For direct field seeding, a 60-h treatment appears optimal, balancing germination enhancement against the risk of seedling mortality under less controlled conditions.

However, several limitations should be acknowledged. The absence of biochemical data (e.g., α -amylase activity, malondialdehyde levels, reactive oxygen species) precludes mechanistic interpretation of priming effects. The lack of soil moisture and temperature records limits understanding of method $\times$ environment interactions. Furthermore, the warning messages regarding insufficient means for *post hoc* comparisons of method (only two levels) are statistical artifacts rather than analytical deficiencies.

Future research should investigate: (1) the physiological mechanisms underlying the divergent secondary root response, (2) the basis for the paradoxical vigour index findings, (3) the identity of the large residual units and their potential exclusion or correction, and (4) dose-response relationships using intermediate treatment durations to identify optimal priming windows with greater precision.

4.5 Conclusions and recommendations

This study demonstrates that both cultivation method and pre-treatment duration significantly influence germination and early seedling growth, with significant interactions between these factors for multiple parameters. Field conditions generally enhance germination and shoot/root growth, whereas pot conditions promote lateral root proliferation. Extended treatment durations up to 60 h improve most parameters under field conditions, whereas 48 h represents the optimal duration for pot conditions. These findings provide evidence-based recommendations for species-specific seed priming protocols tailored to subsequent growing environments. Conclusions can also be drawn that planting the seeds in the summer months between October and November is recommended. This helps to realize the germination and growth potential of marula seedlings.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

SM: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review and editing. PM: Conceptualization, Funding

acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review and editing. VM: Project administration, Supervision, Writing – review and editing. PC: Formal Analysis, Investigation, Methodology, Writing – review and editing. MM: Data curation, Formal Analysis, Investigation, Software, Writing – review and editing. TM: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review and editing.

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