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Influence of Biochar Amendment on Growth Attributes of Sapindus Mukorossi : A Sustainable Approach for Agroforestry Development

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ABSTRACT

This study explores influence of pre-sowing seed treatments and biochar application on the growth and vigour of Sapindus mukorossi Gaertn. seedlings. Various combinations of biochar (soil, sand, FYM, and biochar) were applied in different ratio, alongside pre-sowing treatments, to evaluate their possible impacts on seedling growth attributes, such as, height, collar diameter, root length, leaf area, fresh and dry weight, and vigour indices like root: shoot ratio, sturdiness quotient, and seedling vigour index (SVI). The results revealed significant variations in seedling growth and vigour among different treatments. Biochar, particularly when combined with sand, demonstrated positive effect on seedling growth, enhancing root and shoot development, leaf area, and overall seedling quality. The study suggests that biochar can play a crucial role in enhancing seedling establishment, particularly in nursery settings for S. mukorossi. The findings point the potential of biochar as a valuable substance for enhancing seedling quality in forestry, agroforestry and land restoration projects. Future research is recommended to assess the long-term effects of biochar on soil health, species-specific responses, and its economic feasibility for sustainable environmental management.

INTRODUCTION

The growing global emphasis on sustainable land management and carbon sequestration has highlighted biochar as a promising soil amendment with multifaceted benefits (Kalderis *et al.*, 2024; Smith *et al.,* 2024). Biochar, a carbon-rich material produced through pyrolysis of organic biomass under limited oxygen, has been widely studied for its potential to improve soil fertility, enhance nutrient retention, boost microbial activity, and mitigate greenhouse gas emissions (Atkinson *et al.,* 2010; Biederman and Harpole, 2013, Singh *et al.,* 2022). These attributes make biochar an attractive alternative for improving nursery and plantation practices, particularly in degraded and nutrient-deficient soils.

Biochar has emerged as a promising soil amendment due to its multifunctional role in improving soil fertility, carbon sequestration, and crop productivity. Numerous studies have reported its ability to alter soil physico-chemical characteristics, such as, pH, cation exchange capacity (CEC), water retention, and nutrient availability (Lehmann and Joseph, 2015). Biochar enhances microbial activity, and fosters a more favourable rhizosphere environment, which in turn supports plant growth (Thies *et al.,* 2015; Glaser *et al.,* 2015).

Research on application of biochar in forestry and agroforestry has gained momentum, particularly regarding its influence on seedling development. In *Eucalyptus camaldulensis* and *Dalbergia sissoo*, biochar has been recorded to improve seedling height, root:shoot ratio, and biomass when applied at optimal concentra-

tions (Kumar *et al.,* 2018; Singh *et al.,* 2020). Studies have also highlighted the importance of biochar's feedstock origin and pyrolysis temperature in determining its effectiveness; with woody biochars generally being more stable and nutrient-retentive than those derived from crop residues (Enders *et al.,* 2012). A wide body of research has established the positive impacts of biochar on plant growth, particularly in herbaceous and woody species. Biederman and Harpole (2013) through a meta-analysis, reported significant improvements in plant productivity and nutrient cycling in biochar-amended soils. Major *et al.* (2010) observed increased yield in maize, and nutrient uptake following biochar application in tropical oxisols. In forestry species, studies have shown that biochar application improves seedling vigour, shoot and root biomass, and overall stress tolerance. In context of agroforestry and nursery management, biochar has shown potential in enhancing the early- stage growth of tree seedlings. Mishra *et al.* (2023) observed improved seedling growth for *Hevea brasiliensis* in nursery conditions when biochar was used in combination with nitrogen and magnesium fertilizers. Likewise, Yousaf *et al.* (2021) demonstrated that biochar improved physiological performance and nutrient uptake in *Eucalyptus camaldulensis* grown under saline stress. Research on *Vachellia nilotica* and *Dalbergia sissoo* has also confirmed the positive impact of biochar under stressful soil conditions (Ilaz and Haq, 2021).

Although, substantial research exists on the effects of biochar on agricultural and forest species, limited attention has been given to its influence on *S. mukorossi* Gaertn. (family Sapindaceae), commonly known as the Indian soapnut or *Reetha* , a multipurpose tree species valued for its medicinal properties, soap-producing fruits, and potential role in agroforestry systems. *S. mukorossi* is well-suited for degraded land rehabilitation. However, poor germination rate and slow initial growth hinder its large-scale propagation. Although, biochar can enhance tree seedling growth, particularly in angiosperms and tropical ecosystems, there is a notable lack of research on its application to underutilized species like *S. mukorossi.* Given the ecological and economic importance of this species, especially in reforestation and rural livelihood programmes, exploring the positive impact of biochar-enriched media on its germination and early growth is both timely and relevant. This study aims to investigate the role of biochar as a component in nursery potting mixtures, and assesses its effects on the seedling vigour and growth performance of *S. mukorossi*, thereby contributing to the development of sustainable nursery practices. The study addresses this gap by evaluating how different concentrations of biochar affect key growth attributes of *S. mukorossi*, aiming to establish a sustainable and efficient nursery practice for this underutilized tree species.

MATERIALS AND METHODS

Study Site

The study was conducted during 2022 at the ICAR- Central Agroforestry Research Institute (ICAR- CAFRI), located at an altitude of 211 m asl on rocky terrain in semi-arid Jhansi, Uttar Pradesh, India. The region is heavily dependent on monsoon rains for irrigation, with the rainy season typically beginning in the third week of June. The average annual rainfall in Jhansi is around 1150 mm. The site experiences high summer temperature ranging from 45°C to 49°C, while temperature in winter drops to as low as 0°C. Seed germination studies and seedling growth trials were conducted during May to June 2022 at the ICAR- CAFRI nursery.

Biochar Procurement and Characterization

The biochar used in this study was a mixed wood-coconut husk biochar procured from M/s Anulekh Agrotech Pvt. Ltd., Maharashtra, with support from the International Centre for Research in Agroforestry (ICRAF), New Delhi. The pH of biochar was 9.04 ± 0.011, and the water retention capacity was 106.1% ± 0.011.

Selection of Tree Species

Sapindus mukorossi Gaertn. (Family: Sapindaceae), commonly known as Indian soapberry, was selected for this study. This species thrives in a variety of soils, including sandy, loamy, and clay soils, with pH ranging from mildly acidic to mildly alkaline. It prefers well-drained soil, and can grow in nutritionally-poor soils, making it suitable for cultivation in degraded lands. *S. mukorossi* is a fast- growing tropical deciduous species native to India and Japan, with a potential height of 10-20 m. The plant produces small white flowers arranged in large panicles, and its fruits are yellow to orange in colour. The plant is of great ecological and economic value due to its medicinal properties, use as bioenergy source, and ability to act as a natural wash material, especially for woollens due to its high saponin content. Given its diverse uses and environmental benefits, *S. mukorossi* was chosen for the present study.

Seed Treatment and Preparation of Germination Media

Seeds of *S. mukorossi* were collected manually and sourced from Ch. Sravan Kumar University of Agriculture and Technology, Palampur (Himachal Pradesh). The seeds were stored in well-ventilated conditions in gunny bags until use. For pre-sowing treatment, seeds were given sandbag treatment. In this treatment, the seeds were kept in moist sand bags (1:2 seed-to-sand ratio) for 96 h before sowing, to promote germination.

The germination media were prepared by mixing biochar, soil, sand, and farmyard manure (FYM) in different ratio. The mixtures were filled into perforated polybags (14 cm × 10 cm), kept in a ventilated nursery for seedling growth and vigour studies. Biochar served as a beneficial substitute for sand in the potting medium, improving the substrate's water retention and nutrient content. The polybags were watered regularly before sowing the seeds. The seeds were sown at twice the depth of their size using a stick, and watering was performed once daily.

Experimental Treatments

Seven treatments consisted of different combinations of soil, FYM, sand, and biochar were tested to determine the optimal media for seed germination and seedling growth of *S. mukorossi*. The treatments were: T1: Soil + Sand + FYM (1:1:1); T2: Soil + Biochar + FYM (1:1:1); T3: Soil + Biochar + FYM (1:0.25:1); T4: Soil + Biochar + FYM (1:0.5:1); T5: Soil + FYM (1:1); T6: Sand (100%); and T7: Soil (100%). Each treatment was replicated three times with 18 seeds per treatment (2 seeds per polybag in 9 polybags per treatment). Polybags were filled with these media combinations, and the weight of the dry and wet polybags was measured using a weighing machine.

Seed Sowing and Germination Monitoring

A total of 126 seeds were used for the germination trial. Seeds were sown in polybags, and watered regularly. Observations on germination were recorded daily from the day after sowing (DAS) up to 30 days. Germination was considered complete when the cotyledons of the seeds emerged above the soil surface. Growth parameters, including seedling height, leaf number, and root length were measured after seedlings reached the two-leaf stage.

Nursery Trials

The seed germination trial was laid out in a Completely Randomized Design (CRD) with seven treatments and three replications. Each replication consisted of 18 seeds, and the observations were recorded daily. Similarly, the effect of pre-sowing seed treatments on seedling growth was also assessed using a CRD, with three replications and 18 seedlings per treatment.

After seed germination, the seedlings were monitored for growth parameters in a greenhouse at the ICAR- CAFRI. Key growth parameters assessed include: germination percentage (GP), mean daily germination (MDG), peak value (PV), germination value (GV), mean germination time (MGT), and germination rate index (GRI). Additionally, seedling height, root length, leaf count, biomass, chlorophyll content (measured with a CCM200 Chlorophyll Meter), and root-to-shoot ratio were recorded after 30 days. The seedlings were analyzed for total dry weight (TDW), shoot diameter (SD), aerial part dry weight (ADW), and root dry weight (RDW).

RESULTS AND DISCUSSION

Chemical Composition and Characteristics of Biochar

The chemical analysis of the biochar, as provided by the ICRAF, New Delhi revealed that it contained 40.92% total carbon, 0.75% total nitrogen, 0.18% total phosphorus, 0.95% total potassium, with a cation exchange capacity (CEC) of 23.00 ± 3.49 meq/100g. The pH of the biochar was found to be alkaline in nature (9.04 ± 0.01), indicating its basic characteristic. The water retention capacity of the biochar was estimated to be 106.1% ± 0.01, highlighting its high moisture-holding potential. In terms of polybag weight measurements, treatments incorporating sand exhibited greater weight, compared to those containing biochar and FYM. Among all treatments, the polybags filled with 100% sand recorded the highest weight. Additionally, a general increase in the weight of all polybags was observed following the addition of water.

Seed Germination

The earliest germination was observed on the sixth day after sowing (DAS) in Treatment T6, which consisted solely of sand (Fig.1). This treatment also exhibited the highest overall germination percentage among all the treatments. *S. mukorossi* saplings demonstrated both the earliest onset and the maximum germination rate in the sand-based growing medium, indicating favorable conditions for germination. This was followed by Treatment T1, which comprised of a mixture of soil, sand, and FYM in equal proportions, suggesting that a

balanced medium also supports good germination performance.

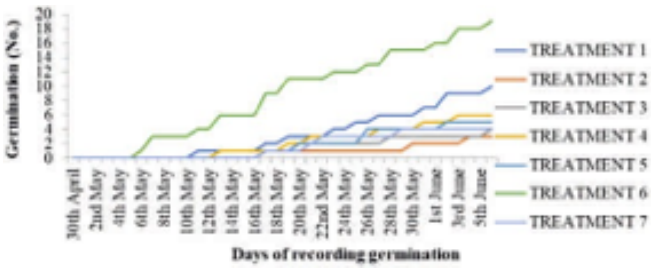


Figure 1: Germination recorded per day for 30 DAS for S. mukorossi.

Influence of Pre-sowing Seed Treatments and Biochar Application on Germination

Seed germination is a critical phase in the regeneration of plant species, and plays a significant role in commercial seedling production. In the present study, the effects of pre-sowing seed treatments and biochar application on various germination parameters - including Germination Percentage (GP), Mean Daily Germination (MDG), Peak Value of Germination (PV), Germination Value (GV), Mean Germination Time (MGT), and Germination Rate Index (GRI)—were assessed, and analyzed statistically (Table 1, Figs. 2 and 3). Germination percentage ranged from 16.67 to 100, with an average of 39.68. The highest germination (100%) was recorded in Treatment T6 (sand only), followed by T1 (soil:sand:FYM 1:1:1 ratio; 55.56%), while the lowest (16.67%) was observed in T4 (soil:biochar:FYM 1:1:1 ratio). Similarly, MDG was highest in T6 (2.63 day^{-1}), followed by T1 (1.46 day^{-1}), and lowest in T2 (0.44 day^{-1}). Peak Value (PV) ranged from 0.46 to 3.06 with the highest recorded for T6 (3.06), followed by T1 (1.47), and the lowest for T2 (0.46). Germination Value (GV) also showed significant variation, with T6 recording the maximum value (8.04), followed by T1 (2.15), and the minimum in T2 (0.20). Mean Germination Time (MGT) varied between 125.62 and 157.41 days, with the shortest duration in T6, and the longest in T2. Germination Rate Index (GRI) ranged from 0.64 to 6.37, with T6 again showing the highest rate, followed by T1 (2.34), while T2 exhibited the lowest rate (0.64).

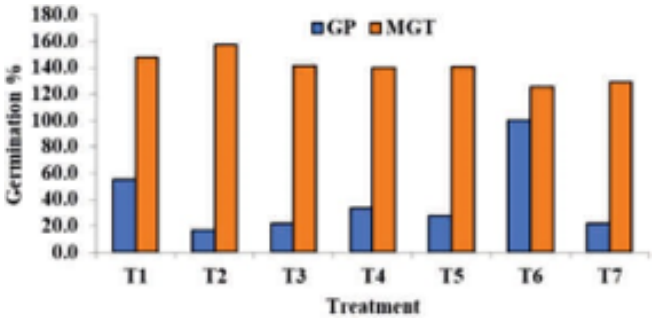


Figure 2: Influence of pre-sowing seed treatment and biochar application on germination time of S. mukorossi at 30 DAS (GP- Germination Percentage, MGT- Mean Germination Time)

Overall, the results demonstrated that T6 (sand) was the most favorable medium for *S. mukorossi* seed germination across all the attributes studied, indicating a more conducive environment in terms of moisture retention, aeration, and absence of inhibitory substances. In contrast, treatments containing biochar, particularly T2 and T4, significantly hindered germination performance. This suggests that these biochar formulations used may not be suitable for *S. mukorossi*, possibly due to species-specific dormancy-breaking requirements, seed coat permeability, or the chemical characteristics of biochar itself. These findings underscore the importance of selecting appropriate potting media and pre-sowing treatments to enhance germination success in nursery conditions.

Influence of Pre-sowing Seed Treatments and Biochar Application in Varying Ratio and Combinations on Seedling Growth of S. mukorossi

The influence of pre-sowing seed treatments and biochar application in different ratio and combinations on the early seedling growth of *S. mukorossi* was assessed using various morphological and physiological parameters for 30 DAS. These include seedling height, collar diameter, number of leaves, leaflet count, leaf area, root length, fresh and dry biomass, and vigour indices, such as, root-to-shoot ratio, sturdiness quotient, and Seedling Vigour Index (SVI). Significant variations were observed across different treatments for seedling height at 30 DAS (Table 2). The maximum seedling height (14.87 cm) was recorded in T1 [Soil:Sand:FYM (1:1:1)], followed by T5 [Soil:FYM (1:1) - height 13.87 cm], while the minimum height (10.27 cm) was observed in T3. The overall mean shoot height was 13.03 cm. Root length was also significantly affected by the treatments. The sand-alone treatment (T6) recorded the highest root length (21.63 cm), followed by T7 (Soil alone; root length 20.23 cm) and T3 [Soil:Biochar:FYM

Table 1: Influence of pre-sowing seed treatment and biochar application on germination atrributes of *S. mukorossi*

Treatment	GP	MDG	PV	GV	MGT	GRI
T1:Soil+Sand+FYM (1:1:1)	55.56	1.46	1.47	2.15	147.78	2.34
T2:Soil+Biochar+FYM (1:1:1)	16.67	0.44	0.46	0.20	157.41	0.64
T3:Soil+Biochar+FYM(1:0.25:1)	22.22	0.58	0.58	0.34	141.67	1.00
T4:Soil+Biochar+FYM (1:0.5:1)	33.33	0.88	0.95	0.84	139.81	1.46
T5:Soil+FYM	27.78	0.73	0.82	0.60	141.11	1.15
T6:Sand alone	100.00	2.63	3.06	8.04	125.62	6.37
T7:Soil alone	22.22	0.58	0.74	0.43	129.17	0.99
Mean±SE	39.68± 29.47	1.04± 0.77	1.16± 0.90	1.80± 2.83	140.37± 10.73	1.99± 2.00

Abbreviations: GP- Germination percentage, MDG- Mean daily germination, PV- Peak value of germination, GV- Germination value, MGT- Mean germination time, GRI- Germination rate index

Table 2: Influence of pre-sowing seed treatments and biochar application on seedling growth attributes of *S. mukorossi*

Total Dry weight (g)	0.57	0.47	0.37	0.35	0.53	0.74	0.79	0.55± 0.17
Total Fresh Weight (g)	2.62	2.45	2.38	1.20	2.40	2.48	3.79	2.48± 0.75
Total Leaf Area (cm2)	46.98	65.35	57.29	93.25	49.03	134.93	131.30	82.5± 37.76
Collar Diameter (mm)	2.67	4.08	4.09	3.81	3.23	4.33	2.57	3.54± 0.7
Chlorophyll Content Index (CCI)	13.18	10.58	2.18	7.40	6.97	7.88	10.47	8.38± 3.5
Dry Shoot Weight (g)	0.41	0.32	0.24	0.21	0.41	0.50	0.59	0.38± 0.1
Dry Root Weight (g)	0.16	0.15	0.13	0.14	0.12	0.24	0.19	0.16± 0.1
Fresh Shoot Weight (g)	1.96	1.69	1.65	0.62	1.96	1.59	2.94	1.77± 0.7
Fresh Root Weight	0.66	0.76	0.73	0.58	0.45	0.88	0.85	0.70± 0.1
Leaflet (No.)	28.33	32.00	27.67	30.00	34.00	34.00	31.33	31.05± 2.5
Leaf (No.)	3.33	3.33	4.00	3.33	4.33	3.67	3.33	3.62± 0.4
Root Length (cm)	17.03	19.83	20.17	14.17	17.50	21.63	20.23	18.6± 2.5
Shoot (cm)	14.87	13.11	10.27	13.70	13.87	13.07	12.37	13.0± 1.4
Treatment	T1	T2	T3	T4	T5	T6	T7	Mean±SD

(1:0.25:1); root length 20.17 cm]. The lowest root length (14.17 cm) was recorded in T4. Collar diameter was found to be maximum in the sand treatment (T6, collar diameter 4.33 mm) and minimum in T7 (Soil alone; collar diameter 2.57 mm). The number of leaves per seedling was highest (4.33) in T5 [Soil:FYM (1:1)] and lowest (3.33) in T7. The sand treatment (T6) recorded maximum number of leaflets (34.00).

Chlorophyll Content Index (CCI), an indicator of photosynthetic potential, varied significantly among the treatments (Table 2). The highest CCI (4.33) was observed in sand treatment (T6), and the lowest (2.57) in soil-alone treatment (T7), with a mean value of 3.45 ± 0.72. Fresh and dry biomass components also exhibited notable differences. At 30 DAS, fresh root weight was highest in T6 (0.88 g), and lowest in T5 (0.45 g), while fresh shoot weight peaked in T7 (2.94 g), and was lowest in T4 (0.62 g). Dry root weight ranged from 0.12 g (T5) to 0.24 g (T6), and dry shoot weight varied from 0.21 g (T4) to 0.59 g (T6). The mean fresh root and shoot weight were 0.70 g and 1.77 g, respectively, while the corresponding dry weight averaged 0.16 g (for root) and 0.38 g (for shoot). Total leaf area also showed significant variation among treatments, ranging from 46.98 cm² to 134.93 cm². The highest leaf area was recorded in T6 (sand treatment), while the lowest was in T1 [Soil:Sand:FYM (1:1:1)]. The mean leaf area was 82.59 ± 37.76 cm². Total fresh plant weight (root + shoot) varied significantly across treatments, with a mean of 2.48 ± 0.75 g. The highest fresh biomass was recorded in T7 (3.79 g), while it was the lowest (1.20 g) in T4 [Soil:Biochar:FYM (1:0.5:1)]. Similarly, total dry weight ranged from 0.35 g (T4) to 0.79 g (T6), with an average of 0.55 ± 0.17 g.

The results, thus, demonstrate that the sand-only treatment (T6) consistently supported better seedling growth in terms of root development, biomass accumulation, and leaf area, likely due to improved aeration and water retention capacity. In contrast, the inclusion of biochar in certain combinations, especially at higher ratio (T4), appeared to impact negatively the early seedling growth, possibly due to changes in nutrient availability, pH, or water-holding characteristics of the growth medium.

Influence of Pre-Sowing Seed Treatments and Biochar Application on Seedling Vigour

The impact of pre-sowing seed treatments and biochar-based substrate combinations on the seedling vigour of *S. mukorossi* was evaluated through key vigour parameters, *viz.* root-to-shoot ratio, sturdiness quotient (SQ), and seedling quality index (SQI) (Fig. 4). Significant variation was observed in the root-to- shoot ratio among treatments, with values ranging from 0.29 to

0.65 (mean: 0.65 ± 0.29). The highest ratio (0.65) was recorded in T4 (Soil:Biochar:FYM, 1:0.5:1), followed by T3 (Soil:Biochar:FYM, 1:0.25:1) with 0.56. The lowest ratio (0.29) was observed in T5 (Soil:FYM, 1:1). A higher root-to- shoot ratio indicates better allocation of biomass towards the root system, enhancing the plant's ability to absorb water and nutrients, especially under field stress conditions The sturdiness quotient (SQ), which reflects the robustness and stability of seedlings, varied significantly across the treatments, ranging from 2.53 to 5.47 (mean: 3.89 ± 1.09). The lowest SQ value (2.53) was recorded in T3, indicating sturdier seedlings, while the highest value (5.47) was observed in T1 (Soil:Sand:FYM, 1:1:1). An SQ value <6.0 is considered desirable for forest species, as it signifies compact and healthy seedlings better suited for survival in field conditions (Jaenicke, 1999; Takoutsing *et al.*, 2014). The SQI, an integrative measure combining multiple morphological parameters, ranged from 0.07 to 0.14, with a mean of 0.09 ± 0.03. The highest SQI was observed for T6 (Sand alone), suggesting that this medium supported the best overall seedling quality. The lowest SQI (0.07) was recorded in treatments T1, T4, and T5. SQI values are closely linked to dry biomass and sturdiness quotient, both were highest in T6, thus, contributing to its superior SQI (Binotto *et al.*, 2010).

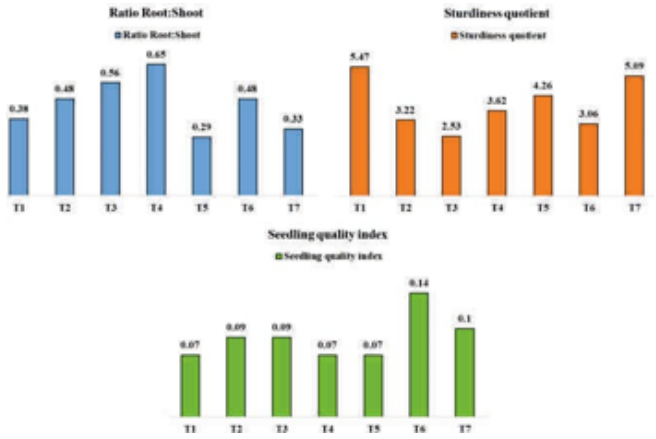


Figure 4: Influence of different pre-sowing seed treatments on root and shoot ratio, sturdiness quotientt, and seedling quality index in S. mukorossi

Overall, the results demonstrated that the pre-sowing seed treatments and growing media compositions significantly influenced the vigour and morphological traits of *S. mukorossi* seedlings at 30 DAS. T6 (Sand alone) consistently promoted superior root development and biomass accumulation, as indicated by parameters, such as, root length (21.63 cm), collar diameter (4.33 mm), root fresh weight (0.88 g), root dry weight (0.24 g), leaflet number (34.00), and survival rate (100%). In contrast, T1 (Soil:Sand:FYM, 1:1:1) recorded the tallest seedlings (height 14.87 cm), while T5 (Soil:FYM, 1:1) exhibited the highest number of leaves per seedling (4.33 leaves). Additionally, chlorophyll content index was highest in T2, and shoot biomass (both fresh and dry) was highest in T7 (Soil alone), with fresh and dry shoot weight of 2.94 g and 0.59 g, respectively.

The improved performance in sand-based treatments can be attributed to better soil aeration and moisture dynamics. Furthermore, the presence of a hard seed coat in *S. mukorossi* plays a critical role in seed germination and subsequent seedling vigour, primarily by modulating water uptake to the embryo. Previous studies (Amirmoradi and Feizi, 2017; Feizi and Javedanipour, 2021) have shown that seedling vigour is inversely related to mean germination time, and seedlings with faster emergence tend to develop more robust root systems. Additionally, the storage of energy reserves in seeds, along with environmental factors, strongly influences early seedling growth. Notably, seed pre-treatment through sandbagging for 96 h was particularly effective in enhancing seedling performance, supporting findings of Amirmoradi and Feizi (2017). The present investigation affirms that an optimal root-to-shoot ratio, sturdiness quotient, and SQI are essential indicators of high-quality seedlings, which are likely to perform better in out-planting conditions.

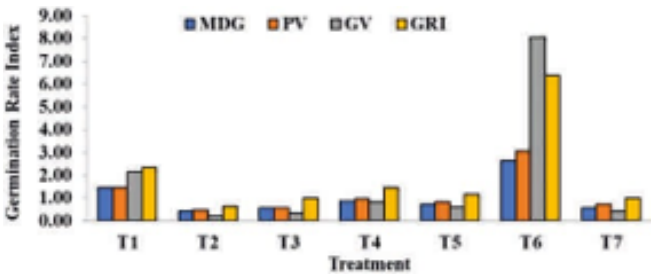


Figure 3: Influence of pre-sowing seed treatment and biochar application on selected germination attributes of S. mukorossi at 30 DAS (MDG- Mean Daily Germination, PV- Peak Value, GV- Germination Value, GRI- Germination Rate Index)

CONCLUSION

The experimental results underline the effectiveness of tailored soil amendments and pre-sowing seed treatments in improving seedling vigour and growth performance of *S. mukorossi*. The study demonstrates that the application of biochar in combination with

soil and FYM significantly affects seedling vigour attributes of *S. mukorossi.* Specifically, the treatment (T4) Soil:Biochar:FYM (1:0.5:1) yielded the highest root-to-shoot ratio (0.65), indicating enhanced root development and potential for better water and nutrient uptake. Although, among the treatments evaluated, sand-alone (T6) consistently provided the best outcome in terms of biomass allocation, morphological traits, and survival rate, making it a highly suitable medium for nursery propagation of *S. mukorossi.* Additionally, the integration of biochar in specific ratio with soil and FYM also showed promising effects on seedling quality, particularly in enhancing root development and seedling sturdiness.These findings suggest that biochar, when applied in appropriate proportions, can be a valuable soil amendment to enhance root architecture, sturdiness, and seedling vigour, especially when integrated with organic matter like FYM. The enhanced porosity, cation exchange capacity, and water-holding ability of biochar may have contributed to improved seedling performance in biochar treatments (Lehmann and Joseph, 2015; Glaser *et al.,* 2015). The findings also suggest that physiological seed dormancy in *S. mukorossi* can be effectively managed through pre-sowing treatments, such as, sand bagging, which enhances germination and subsequent growth. In conclusion, optimizing growing media composition along with appropriate seed pre-treatment can significantly enhance the nursery performance of *S. mukorossi* Future studies may explore the long-term impact of these treatments on field establishment and survival, and assess their implications under different climatic regimes.

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