The Original

EFFECT OF SEED SOURCE AND SOWING SEASON ON NURSERY PRODUCTION OF INDIAN SANDALWOOD (*SANTALUM ALBUM* L.) UNDER SUBTROPICAL CONDITIONS OF JAMMU, INDIA

Rahul Sharma[1], S K Gupta[2], L M Gupta[3], Manjot Singh[4], Sourav Singh[5], Lalit Upadhyay[6*]

[1]Research Scholar, Division of Silviculture & Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, India, Email- rsrahulss92@gmail.com
[2]Research Scientist, Division of Silviculture & Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, India, Email-sushilgupta67g@gmail.com
[3]Research Scientist, Division of Forest Products and Utilization, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, India, Email- guptalm@gmail.com
[4]Research Scholar, Division of Silviculture & Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, India, Email-manjotsidhu58@gmail.com
[5]Research Scholar, Division of Silviculture & Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, India, Email-s7.manhas75@gmail.com
[6*]Research Scientist, KVK Reasi, Division of Silviculture & Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, India, Email-lalitkvkr@skuastj.org
*Corresponding Author: Email: lalitkvkr@skuastj.org

ABSTRACT
Indian sandalwood (*Santalum album* L.), a hemi-parasitic tree species, is being cultivated beyond its range in India. However, information on seed sources and sowing seasons for nursery germination under subtropical conditions remains limited. This study evaluated the effect of seed source and sowing season on germination performance of *S. album* under nursery conditions in Jammu, India. The experiment was conducted in a factorial randomized design comprising two sowing seasons (spring and rainy) and four seed sources: Mysore (Karnataka), Coimbatore (Tamil Nadu), Idukki (Kerala), and Hamirpur (Himachal Pradesh), with five replications. Germination percentage, germinative energy, coefficient of velocity of germination (CVG), mean daily germination (MDG), and mean germination time (MGT) were recorded. Sowing season and seed source significantly affected germination parameters. Spring sowing resulted in superior germination performance compared with rainy-season sowing. Among seed sources, Mysore (Karnataka) exhibited the best performance, followed by Coimbatore (Tamil Nadu) and Idukki (Kerala), whereas Hamirpur (Himachal Pradesh) performed poorest. The interaction between sowing season and seed source was significant for CVG and MGT, with Mysore seeds under spring sowing showing highest CVG and shortest MGT. These findings provide a basis for selecting seed sources and sowing seasons for nursery germination of sandalwood under subtropical conditions.

KEYWORDS: Germination; nursery germination; Santalum album; seed source; sowing season; subtropical India.

1. INTRODUCTION
Indian sandalwood (*Santalum album* L.), a member of the family Santalaceae, is a high-value evergreen hemi-parasitic tree renowned for its fragrant heartwood and essential oil rich in α- and β-santalol (Chouhan & Solanki, 2026; Wadichar et al., 2025). The species is widely valued in the perfumery, pharmaceutical, cosmetic, handicraft and traditional medicine industries, making it one of the most economically important tropical tree species (Arunkumar et al., 2012; Chavan et al., 2024). Naturally distributed in peninsular India, particularly in Karnataka, Tamil Nadu and Kerala, *Santalum album* contributes significantly to the forest-based economy and rural livelihoods (Chavan et al., 2024; Srikantaprasad et al., 2022). Rising global demand for sandalwood products has further increased its commercial importance, with the global sandalwood oil market projected to reach approximately USD 197 million by 2026 (Kaur et al., 2025). However, natural populations have declined considerably due to indiscriminate harvesting, poor natural regeneration, diseases, changing land-use patterns and climatic variability, resulting in the species being classified as Vulnerable on the IUCN Red List (Kumar et al., 2019). These challenges highlight the urgent need for sustainable propagation strategies and the production of high-quality planting stock to support conservation, afforestation, agroforestry and commercial plantation programmes. Improving nursery efficiency through identification of superior reproductive material is a fundamental component of sustainable forest management, as it enhances plantation success, reduces resource wastage and supports conservation-oriented cultivation of threatened tree species.
In response to declining natural resources and increasing market demand, sandalwood cultivation is expanding beyond its native distribution into non-traditional agro-climatic regions of India. Successful plantation establishment depends largely on the availability of healthy nursery stock, while seed germination in *Santalum album* may vary with seed dormancy,

seed source and environmental conditions during sowing (Das & Tah, 2017). Previous studies have demonstrated that seed source significantly influences germination, seed vigour and early seedling growth, with Karnataka seed sources generally exhibiting superior nursery performance (Annapurna et al., 2006; Shwetha et al., 2024). Likewise, sowing season plays a critical role by regulating soil temperature, moisture availability and aeration, thereby influencing germination rate, uniformity and early seedling establishment (Mohapatra et al., 2019; Verma, 2022).

Although considerable progress has been made in developing nursery practices for sandalwood in southern India, information on the combined influence of seed source and sowing season under the subtropical conditions of northern India remains limited. Moreover, region-specific recommendations for producing quality planting stock are lacking despite the increasing cultivation of *Santalum album* outside its natural range, including parts of Himachal Pradesh (Dutt & Verma, 2005; Dutt et al., 2021). Therefore, the present study was undertaken to evaluate the influence of four seed sources and two sowing seasons on the germination performance of Indian sandalwood under nursery conditions in the Jammu subtropics. The findings will help identify suitable seed source and sowing season combinations for improving nursery germination and provide scientific guidance for sandalwood production and expansion under subtropical conditions of northern India.

2. MATERIALS AND METHODS

Study area

The nursery experiment was conducted during 2023 and 2024 at the experimental farm of the Division of Silviculture and Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu (SKUAST-J), Chatha, Jammu and Kashmir, India. The experimental site is located in the subtropical agro-climatic zone at an altitude of 332 m above mean sea level (MSL) (32°40′15″ N, 74°58′04″ E) (Fig. 1). The region experiences hot, dry summers, humid monsoons and cool winters. Summer temperatures may reach 46 °C, whereas winter temperatures occasionally fall below 4 °C. The majority of the annual precipitation is received during the southwest monsoon (July-August), resulting in distinct seasonal conditions at the experimental site (Fig. 2).

Experimental design

The experiment was laid out in a factorial completely randomized design (CRD) comprising two experimental factors: seed source (four levels) and sowing season (two levels). The four seed sources included Mysore (Karnataka), Coimbatore (Tamil Nadu), Idukki (Kerala) and Hamirpur (Himachal Pradesh), while the two sowing seasons were spring (ST-1) and rainy season (ST-2). The seed sources from Mysore (Karnataka), Coimbatore (Tamil Nadu) and Idukki (Kerala) were selected because they represent the principal natural distribution range of *Santalum album* in India. Hamirpur (Himachal Pradesh) was included because previous introduction efforts have demonstrated successful establishment and adaptation of sandalwood under the subtropical conditions of northwestern India, making it an important comparative seed source for the present investigation. The experiment consisted of eight treatment combinations with five replications (Table 1). Each replication comprised 50 seeds, resulting in 250 seeds per treatment. Sowing was carried out during March (spring season) and June (rainy season) in both 2023 and 2024. Germination observations were recorded daily for 45 days after sowing. The details of experimental and statistical design as under:

Experimental Design:	**Factorial CRD**
Factors:	Seed source (4) x Sowing season (2)
Treatment combination:	8
Number of replications:	5
Seeds per replication:	50
Total seeds per treatment:	250
Date of sowing:	15th March and 19th June, 2023 11th March and 12th June, 2024

Seed collection and quality standardization

Seeds from Mysore (Karnataka), Coimbatore (Tamil Nadu) and Idukki (Kerala) were procured from established sandalwood sources, whereas seeds from Hamirpur (Himachal Pradesh) were collected directly from established sandalwood plantations in the region. Seed lots harvested during October 2022 were used for the experiments conducted in 2023, whereas seed lots harvested during October 2023 were used for the experiments conducted in 2024 ensuring that all seed sources used within each experimental year originated from the same fruiting season. Before sowing, all seed lots were visually examined and standardized by removing damaged, malformed and undersized seeds to obtain uniform planting material. Only healthy and uniform seeds were used in the experiment to minimize variability attributable to seed quality.

Nursery bed preparation and seed sowing

Raised nursery beds of 3 m × 1 m (approx. 10 ft. × 3 ft.) were prepared separately for each sowing season using a potting mixture of sand, soil, and well-decomposed farmyard manure (2:1:1, v/v/v). Prior to sowing, nursery beds were treated as a prophylactic measure against soil-borne pests. Seeds were soaked in 0.05% gibberellic acid (GA_3) solution for 24-36 hours to enhance germination. Floating seeds were discarded and the remaining seeds were treated with 0.25% Dithane M-45 and 0.1% Carbendazim to minimize fungal infection during germination. All seed lots received identical pre-sowing treatments to eliminate variation arising from seed treatment practices and to minimize variation arising from seed treatment practices and ensure consistency in pre-sowing treatment across all seed sources and sowing seasons. Seeds were sown at a depth of approximately 2 cm in rows spaced 20 cm apart, maintaining a spacing of 6 cm between adjacent seeds within each row. The nursery beds were covered with straw immediately after sowing to conserve soil moisture and were uncovered following seed emergence. Preventive fungicidal sprays of 0.25% Dithane M-45 and 0.02% hexaconazole were applied at fifteen-day intervals. Irrigation was provided once or twice daily using a watering can, depending on prevailing weather conditions.

Germination parameters

Seed germination was monitored daily for 45 days after sowing. Germination percentage (GP), germinative energy (GE), coefficient of velocity of germination (CVG), mean daily germination (MDG) and mean germination time (MGT) were determined using standard procedures. Germination percentage was calculated as the proportion of germinated seeds relative to the total number of seeds sown. Germinative energy was determined as the percentage of seeds that germinated by the day on which germination reached its maximum rate. Mean daily germination was calculated according to Esechie (1994), coefficient of velocity of germination according to Jones and Sanders (1987) and mean germination time according to Orchard (1977) using the following formulae:

$$\text{Coefficient of velocity germination} = \frac{\sum \text{Ni}}{\sum \text{NiTi}} \text{ x } 100$$

Where, Ni = Number of seed germination on ith day (i = 1,2,3….x)

Ti = Number of days from the start of the experiment (i = 1,2, 3…..x)

$$\text{Mean Germination Time (MGT)} = \frac{\sum \text{Ni Ti}}{\sum \text{Ni}}$$

Where, Ni = Number of seeds germinated on ith day (i = 1, 2, 3….x)

Ti = Number of days from the start of the experiment (i = 1,2, 3….x)

Statistical analysis

The experimental data were subjected to two-way ANOVA following a factorial CRD to determine the main effects of seed source, sowing season and their interaction on germination parameters. Treatment means were compared using the critical difference (CD) at the 5% level of significance. Heat map, hierarchical cluster analysis, interaction plots and principal component analysis (PCA) were used to visualize patterns among seed source × sowing season combinations and germination traits. All analyses were performed using R software version 4.6.1.

3. RESULTS

The germination parameters of sandalwood (*Santalum album* L.) as influenced by sowing season and seed source are presented in Table 2. Germination characteristics differed significantly with sowing season and seed source, whereas their interaction was significant only for coefficient of velocity of germination (CVG) and mean germination time (MGT).

Germination percentage

Spring sowing (ST-1) resulted in a significantly higher germination percentage (46.85%) than rainy season sowing (ST-2) (34.75%). Among the seed sources, Mysore (Karnataka) (SS1) recorded the highest germination percentage (45.70%), which was statistically at par with Coimbatore (Tamil Nadu) (SS2) (43.10%). In contrast, Hamirpur (Himachal Pradesh) (SS4) exhibited the lowest germination percentage (33.20%). The interaction between sowing season and seed source had no significant effect on germination percentage.

Germinative energy

Germinative energy was significantly higher under spring sowing (ST-1) (21.35%) than under rainy season sowing (ST-2) (14.80%). Among the seed sources, Mysore (Karnataka) (SS1) recorded the highest germinative energy (21.00%), which was statistically superior to Coimbatore (Tamil Nadu) (SS2) (19.00%) and Idukki (Kerala) (SS3) (18.00%). The lowest germinative energy was observed in Hamirpur (Himachal Pradesh) (SS4) (14.30%). The interaction between sowing season and seed source was non-significant.

Coefficient of velocity of germination (CVG)

The coefficient of velocity of germination was significantly higher under spring season sowing (ST-1) (3.10) than under rainy season sowing (ST-2) (2.76). Among the seed sources, Mysore (Karnataka) (SS1) recorded the highest CVG (3.18), followed by Coimbatore (Tamil Nadu) (SS2) (3.02), Idukki (Kerala) (SS3) (2.89) and Hamirpur (Himachal Pradesh) (SS4) (2.62). The interaction between sowing season and seed source was significant (Fig. 3), with the highest CVG recorded under the ST-1 × SS1 treatment combination (3.39), whereas the lowest value was observed under ST-2 × SS4 (2.55).

Mean daily germination (MDG)

Mean daily germination (MDG) was significantly higher under spring sowing (ST-1) (0.52) than under rainy season sowing (ST-2) (0.40). Among the seed sources, Mysore (Karnataka) (SS1) recorded the highest MDG (0.50), which was statistically at par with Coimbatore (Tamil Nadu) (SS2) (0.48), whereas Hamirpur (Himachal Pradesh) (SS4) recorded the lowest value (0.40). The interaction between sowing season and seed source had no significant effect on MDG.

Mean germination time (MGT)

Mean germination time (MGT) was significantly lower under spring sowing (ST-1) (32.46 days) than under rainy season sowing (ST-2) (36.37 days). Among seed sources, Mysore (Karnataka) (SS1) recorded the shortest MGT (31.67 days), followed by Coimbatore (Tamil Nadu) (SS2) (33.21 days), Idukki (Kerala) (SS3) (34.72 days) and Hamirpur (Himachal Pradesh) (SS4) (38.06 days). A significant interaction between sowing season and seed source was observed (Fig. 4), with the shortest MGT under the ST-1 × SS1 treatment combination (29.54 days) and the longest under ST-2 × SS4 (39.24 days).

Heat Map and Hierarchical Cluster Analysis

To obtain an integrated understanding of germination behaviour among different seed source × sowing season combinations, a heat map coupled with hierarchical cluster analysis was performed using five germination parameters, namely germination percentage (GP), germination energy (GE), coefficient of velocity of germination (CVG), mean daily germination (MDG) and mean germination time (MGT) (Fig. 5). Prior to clustering, all variables were standardized using Z-score transformation, where red indicates relatively higher values and blue indicates relatively lower values for each germination parameter.

The hierarchical clustering separated the eight treatment combinations into two major groups according to their overall germination performance. One cluster predominantly consisted of the spring-sown treatments, particularly SS1_ST-1 (Mysore-Spring), SS2_ST-1 (Coimbatore-Spring) and SS3_ST-1 (Idukki-Spring), which were characterized by higher GP, GE, CVG and MDG values together with lower MGT, indicating superior and faster germination. Among these, SS1_ST-1 and SS2_ST-1 exhibited the greatest similarity in their germination responses, reflecting comparable seed performance.

The second cluster mainly included the rainy-season treatments along with SS4_ST-1 (Hamirpur-Spring), which generally exhibited comparatively lower GP, GE, CVG and MDG values and relatively higher MGT. Within this group, SS4_ST-2 (Hamirpur-Rainy) showed the least favourable germination performance, characterized by the highest MGT and the lowest values of GP, GE, CVG and MDG.

Overall, the clustering pattern indicated that spring sowing promoted better germination performance than rainy-season sowing across the seed sources. Furthermore, the heat map clearly demonstrated the superiority of the Mysore and Coimbatore seed sources under spring sowing conditions, whereas the Hamirpur seed source, particularly under rainy-season sowing, exhibited comparatively poor germination performance.

Principal component analysis (PCA) biplot

The principal component analysis (PCA) biplot illustrated the association among different seed sources, sowing seasons, and germination attributes of *Santalum album* L. under Jammu subtropical conditions (Fig. 6). The first two principal components (PC1 and PC2) explained the major proportion of variation present in the dataset and effectively differentiated the seed source × sowing season combinations based on their germination performance.

The vectors representing germination percentage (GP), germination energy (GE), mean daily germination (MDG), and coefficient of velocity of germination (CVG) showed positive association with PC1, indicating that these traits contributed substantially towards discrimination of superior treatments. The close clustering and similar direction of GP, GE, and MDG vectors indicated a strong positive correlation among these germination parameters, suggesting that treatments with higher germination percentage also exhibited improved germination speed and uniformity.

Among different treatments, SS3_ST-1 (Kerala seed source under spring sowing) was positioned in the positive quadrant of PC1 and PC2, showing a strong association with GP, GE, and MDG. This indicates better germination performance under spring sowing conditions. Similarly, SS1_ST-1 (Mysore seed source under spring sowing) was located towards the positive side of PC1, reflecting superior germination characteristics compared with most other treatments.

The SS4_ST-1 (Himachal Pradesh seed source under spring sowing) treatment showed a distinct position along the positive direction of PC2 and was associated with mean germination time (MGT), reflecting relatively longer germination time. Treatments subjected to rainy-season sowing (ST-2) were generally positioned towards the negative side of PC1, indicating comparatively lower contribution towards favourable germination traits. This separation suggests that sowing season significantly influenced seed germination behaviour, with spring sowing providing more favourable conditions for rapid and uniform germination.

The CVG vector showed an opposite orientation to MGT, indicating their negative relationship. This confirms that treatments exhibiting faster germination had higher germination velocity and reduced time required for seed emergence. The PCA further illustrated the differential responses of seed source × sowing season combinations, with better-performing seed sources generally associated with spring sowing conditions.

4. DISCUSSION

The main effect of sowing season showed that all measured germination parameters were significantly superior under spring sowing (ST-1) compared with rainy-season sowing (ST-2). This may be attributed to the favourable environmental conditions prevailing during spring, including optimum soil temperature, improved aeration and better drainage, which collectively promote rapid and uniform seed germination. In contrast, excessive rainfall during the rainy season may lead to temporary waterlogging and reduced soil aeration, thereby adversely affecting germination and early seedling establishment. In the present study, seeds sown during spring germinated by mid-May, whereas rainy-season sowing (mid-July) coincided with periods of high rainfall that likely created less favourable conditions for germination. Similar observations were reported by Mohapatra et al. (2019), Verma (2022) and Dutt (2000), who concluded that April-May represents the optimum sowing period for successful nursery establishment of sandalwood.

Another possible reason for the superior germination observed under spring sowing is the comparatively shorter storage duration of the seeds before sowing. The seeds used in the present investigation were during October-November harvested and possessed high initial germinative potential. The same seed lot was used for both sowing seasons; therefore, seeds sown during spring experienced a shorter storage period and consequently may have retained higher physiological viability. In contrast, prolonged storage until the rainy season may have resulted in gradual deterioration in seed vigour and germination potential. Thus, the higher germination observed during spring may reflect both more favourable nursery environmental conditions and the shorter storage period preceding sowing, as these factors could not be completely separated under the present experimental schedule. Similar findings were reported by Gamage et al. (2010), who observed a progressive decline in sandalwood seed germination with increasing storage duration, with maximum germination recorded after short-term storage combined with GA3 treatment and negligible germination after prolonged storage.

Significant variation was also observed among the different seed sources. The Mysore (Karnataka) seed source consistently recorded the highest germination percentage, germinative energy, coefficient of velocity of germination and mean daily germination, together with the lowest mean germination time. Such variation among seed sources may be associated with differences in genetic constitution, seed-source characteristics, environmental conditions during seed development, altitude, rainfall pattern, soil properties and the physiological condition of the mother trees (Vakshasya et al., 1992). Seed quality is strongly influenced by genetic factors as well as the age, health and habitat of the mother tree, which ultimately determine seed maturity, viability and germination behaviour (Veerendra et al., 1990). The superior performance of the Karnataka seed source is consistent with earlier reports by Shwetha et al. (2024), Annapurna et al. (2006) and Ramalakshmi and Rangaswamy (1998), who also reported higher germination and seed viability in Karnataka seed sources than in other sandalwood populations. Karnataka, together with Tamil Nadu and Kerala, represents the principal natural distribution range of *Santalum album* in India, where large and well-established natural populations occur (Vignesh et al., 2022; Doddabasawa & Chittapur, 2021). Long-term adaptation to favourable ecological conditions and the availability of healthy mother trees, may have contributed to the production of physiologically superior seeds with greater germination potential. In contrast, the comparatively poor performance of the Hamirpur (Himachal Pradesh) seed source may be associated with differences among seed sources and environmental conditions during seed development, which may influence seed maturity and physiological quality.

The significant interaction observed for the coefficient of velocity of germination and mean germination time indicates that the germination response of different seed sources was influenced by the prevailing sowing season. The higher CVG and shorter MGT observed for the Mysore (Karnataka) seed source under spring sowing indicate that this seed source responded favourably under the environmental conditions prevailing during spring. Similar observations were reported by Kaur et al. (2025), who found that sandalwood seeds sown between mid-March to mid-April exhibited earlier germination and completed the germination process more rapidly than those sown at other times. The authors attributed this response to favourable environmental conditions, particularly mean temperatures ranging from 24 to 30°C, which promoted faster and more uniform germination, whereas temperature extremes delayed both the initiation and completion of germination. These findings are consistent with the present investigation, where spring sowing provided more favourable environmental conditions for germination than rainy-season sowing. Conversely, the decline in germination performance under rainy-season sowing indicates that less favourable environmental conditions may reduce the germination response even among better-performing seed sources. This interaction highlights the importance of integrating the selection of suitable seed sources with an appropriate sowing season and nursery management practices to maximize germination efficiency and produce high-quality planting stock for sustainable sandalwood cultivation.

The multivariate analyses further corroborated the univariate results. Heat map and hierarchical cluster analysis grouped the spring-sown treatments, particularly the Mysore and Coimbatore seed sources, within the superior performance cluster, whereas the Hamirpur seed source under rainy-season sowing formed the least favourable group. Similarly, principal component analysis clearly separated the high-performing southern seed sources from the comparatively poorer-performing Himachal Pradesh seed source, revealing clear multivariate differences among seed source × sowing season combinations based on their overall germination profiles. The consistency between multivariate and univariate analyses strengthens the interpretation of the observed treatment patterns and provides an integrated view of variation in germination behaviour.

Overall, the present study demonstrates that both seed source selection and sowing season are important factors influencing nursery germination of *Santalum album* L. under Jammu subtropics. Mysore (Karnataka) seed source, particularly under spring sowing, exhibited the most favourable overall germination performance under the conditions tested, indicating the potential value of selecting suitable seed sources in combination with an appropriate sowing season to improve nursery germination and planting-stock production. These findings provide practical guidance for nursery managers and silviculturists in selecting suitable seed sources and sowing seasons to improve sandalwood germination under subtropical conditions of northern India.

5. CONCLUSION

The present study demonstrated significant variation in the germination performance of *Santalum album* with respect to seed source and sowing season under subtropical nursery conditions of Jammu. Spring sowing resulted in higher germination percentage, germinative energy, coefficient of velocity of germination and mean daily germination, together with shorter mean germination time, compared with rainy-season sowing. Among the seed sources, Mysore (Karnataka) exhibited the most favourable overall germination performance, whereas Hamirpur (Himachal Pradesh) showed comparatively lower performance. The significant interaction between seed source and sowing season for coefficient of velocity of germination and mean germination time further indicated that germination response varied according to the combination of seed source and sowing season. Overall, the findings indicate that selection of suitable seed sources, particularly Mysore (Karnataka), in combination with spring sowing can improve sandalwood nursery germination under subtropical conditions of northern India. These findings provide a useful basis for nursery planning and selection of suitable seed source × sowing season combinations for sandalwood establishment under similar agro-climatic conditions.

Acknowledgement:
The authors express their sincere gratitude to the Division of Silviculture and Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu for providing the necessary facilities, infrastructure and academic support to carry out this research.

Conflict of Interest:
The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Funding
No specific funding was received for the research reported in this article.

Generative AI Statement
The authors used a generative AI tool solely for language editing and improving the clarity and presentation of the manuscript. The authors reviewed and verified all AI-assisted content and take full responsibility for the final content, accuracy, and integrity of the manuscript.

Data Availability Statement
The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions
Rahul Sharma: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing - original draft, Writing – review & editing. S K Gupta: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. L M Gupta: Methodology, Validation, Writing – review & editing. Manjot Singh: Investigation, Data curation, Writing – review & editing. Sourav Singh: Investigation, Data curation, Visualization, Writing – review & editing. Lalit Upadhyay: Investigation, Resources, Project administration, Supervision, Writing – review & editing.

REFERENCES

1. Annapurna, D., Rathore, T. S. & Joshi, G. (2006). Modern nursery practices in the production of quality seedlings of Indian sandalwood (*Santalum album* L.): stage of host requirement and screening of primary host species. Journal of Sustainable Forestry, 22(3-4), 33-55.
2. Arunkumar, A. N., Joshi, G. & Mohanram, H. Y. (2012). Sandalwood: history, uses, present status and the future. Current Science, 103(12), 1408-1416.
3. Balasubramanian, A., Hariprasath, C. N., Manivasakan, S. & Radhakrishnan, S. (2018). Influence of host on the early growth performance of sandal tree (Santalum album) grown in farm settings. International Journal of Ecology and Environmental Sciences, 44(4), 369-372.
4. Chavan, S. B., Uthappa, A. R., Chichaghare, A. R., Ramanan, S., Kumar, R., Keerthika, A., Arunachalam, A., Hegde, R., Jinger, D., Meena, V. S., Kumar, M., Harisha, C. B., Kakade, V. D., Morade, A. S., Rawale, G. B., Singh, R. & Reddy, K. S. (2024). Past, present and future of Indian sandalwood (Santalum album) cultivation and commercial prospects. Discover Applied Sciences, 6, 627.
5. Chouhan, R. & Solanki, P. (2026). Phytochemistry and pharmacology of *Santalum album* L.- a review. Technix International Journal for Engineering Research, 13(3), 648-654.
6. Das, S. C. & Tah, J. (2017). Role of host plants for white sandal (*Santalum album* L.) cultivation in West Bengal. Asian Journal of Science and Technology, 8(10), 6060-6067.
7. Doddabasawa. & Chittapur, B. M. (2021). Sandalwood plantations-points to ponder. Current Science, 120, 1184-1193.
8. Dutt, S. (2000). Present status, nursery and plantation technology of sandalwood (*Santalum album* Linn.) in low hills of Himachal Pradesh. [Doctoral dissertation, Dr. Y. S. Parmar University of Horticulture and Forestry].
9. Dutt, S. & Verma, K. S. (2005). Effect of collection time, pre-sowing treatments and sowing time on the germinability of sandal (*Santalum album* L.) seeds under nursery conditions. Journal of Non-Timber Forest Products, 12(4), 205-208.
10. Dutt, S., Sharma, K., Sharma, V. & Dhiman, V. (2021). Status of sandalwood (*Santalum album* L.) in low hills of Himachal Pradesh. International Journal of Economic Plants, 8(4), 201-206.
11. Esechie, H. (1994). Interaction of salinity and temperature on the germination of sorghum. Journal of Agronomy and Crop Science, 172, 194-199.
12. Gairola, S., Aggarwal, P. S. & Ravikumar, G. S. (2008). Status of production and marketing of sandalwood (*Santalum album* L.). In Proceedings. national seminar on conservation, improvement, cultivation and management of sandal. Institute of Wood Science and Technology, Bangalore (IWST), 3, 1-8.

13. Gamage, Y. M. M., Subasinghe, S. M. C. U. P. & Hettiarachchi, D. S. (2010). Change of seed germination rate with storage time of *Santalum album* L. (Indian sandalwood) seeds. Proceedings of the 15th International Forestry and Environment Symposium, 15, 279-281.
14. Institute of Wood Science and Technology (IWST). 2014. Sandalwood information system. Indian Council of Forestry Research and Education (ICFRE). https://iwst.icfre.gov.in/database/SIS/index.html.
15. Jones, K. W. & Sanders, D. C. (1987). The influence of soaking pepper seed in water or potassium salt solutions on germination at three temperatures. Journal of Seed Technology, 11, 97-102.
16. Kaur, H., Kaur, N., Singh, B., Gill, R.I.S. & Singh, A. (2025). Impact of sowing time on sandalwood (Santalum album) seedling growth in sub-tropical zone. Indian Journal of Ecology, 52(6), 1492-1498
17. Mohapatra, S. R., Bhol, N. & Nayak, R. K. (2019). Standardization of nursery media and sowing time for germination of sandalwood (*Santalum album* L.) seed. Indian Forester, 145(8), 752-756.
18. Orchard, T. (1977). Estimating the parameters of plant seedling emergence. Seed Science and Technology, 5, 61–69.
19. Ramalakshmi, S. & Rangaswamy, C. R. (1998). Physiological variations in seeds of provenances of sandal (*Santalum album* L.). In Radomiljac, A. M., Ananthapadmanabho, H. S., Welbourn, R. M. & Rao, K. S. (Eds.), Proceedings of Sandal and its Products (pp.121-123). Institute of Wood Science and Technology (ICFRE) & Karnataka State Forest Department.
20. Rao, M. N., Ganeshaiah, K. N. & Shaanker, R. U. (2007). Assessing threats and mapping sandalwood (*Santalum album* L.) resources in peninsular India: identification of genetic hot-spot for in-situ conservation. Conservation Genetics, 8, 925-935.
21. Ratnaningruma, Y. W. N. & Indrioko, S. (2014). Response of flowering and seed production of sandalwood (*Santalum album* Linn., Santalaceae) to climate change. Procedia Environmental Sciences, 28, 665-675.
22. Sahu, S., Maheswarappa, V., Hedge, R., Kencharaddi, R. N. & Sathish, B. N. (2021). Effect of host plants and potting mixture on growth of sandalwood seedlings at nursery stage. International Journal of Current Microbiology and Applied Sciences, 10(09), 545-559.
23. Sandeep, C. & Manohara, T. N. (2019). Sandalwood in India: historical and cultural significance of *Santalum album* L. as a basis for its conservation. NeBIO-An International Journal of Environment and Biodiversity, 10(4), 235-241.
24. Sharma, D. & Kumari, D. (2022). Lantana camara as a potential secondary host for natural populations of *Santalum album* in foothills of Himalayas: a hope to stand along with noxious weed. Biological Forum - An International Journal, 14(3), 179-183.
25. Shwetha, V. R., Mahadevamurthy, M., Raghu, H. B. & Lalitha, B. S. (2024). Assessment of potential seed sources from Karnataka for the production of quality planting stock in *Santalum album* L. Mysore Journal of Agricultural Sciences, 58(1), 285-294.
26. Srikantaprasad, D., Gowda, A. P. M., Pushpa, T. N., Thimmagowda, K., Ravikumar, R. L. & Prasanna, K. T. (2022). Identification of suitable host for sandalwood cultivation in Northern dry zone of Karnataka. Industrial Crops & Products, 182, 114874. 10.1016/j.indcrop.2022.114874
27. Srinivasan, V. V., Sivaramakrishnan, V. R., Rangaswamy, C. R., Ananthapadmanabha, H. S. & Shankaranarayana, K. H. (1992). Sandal; *Santalum album* Linn. Institute of Wood Science and Technology (IWST). Indian Council of Forestry Research and Education.
28. Vakshasya, R. K., Rajora, O. P. & Rawat, M. S. (1992). Seed and seedling traits of Dalbergia sissoo seed source variation studies among ten sources in India. Forest Ecology and Management, 48, 265-275. 10.1016/0378-1127(92)90149-4
29. Veerandra, S. C. H. & Sarma, C. R. (1990). Variation studies in sandal (*Santalum album* L.). Time of emergence and seedling vigor. Indian Forester, 116(7), 568-571. https://doi.org/10.36808/if/1990/v116i7/8872
30. Verma, S. (2022). Studies on population dynamics and nursery performance of *Santalum album* Linn. in Himachal Pradesh. [Doctoral dissertation, Dr. Y. S. Parmar University of Horticulture and Forestry].
31. Wadichar, S., Dhokane, P., Tirmanwarr, S., Pondhe, G., Kolaskar, S. & Tarahane, S. (2025). Sandalwood: A phytochemical and pharmacological Overview. International Journal of Pharmaceutical Sciences, 3(01), 334-341. https://doi.org/ 10.5281/zenodo.14605347

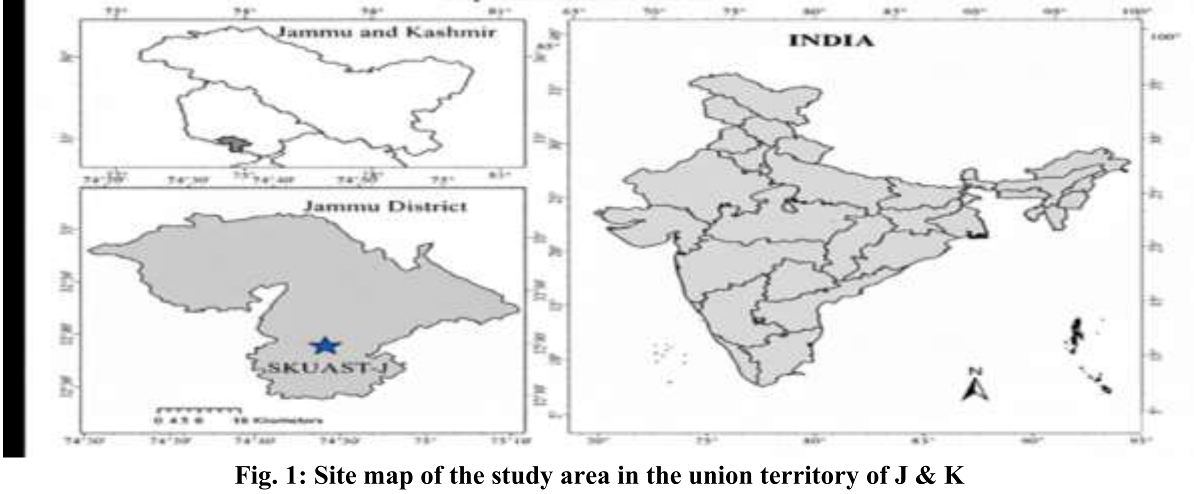

Fig. 1: Site map of the study area in the union territory of J & K

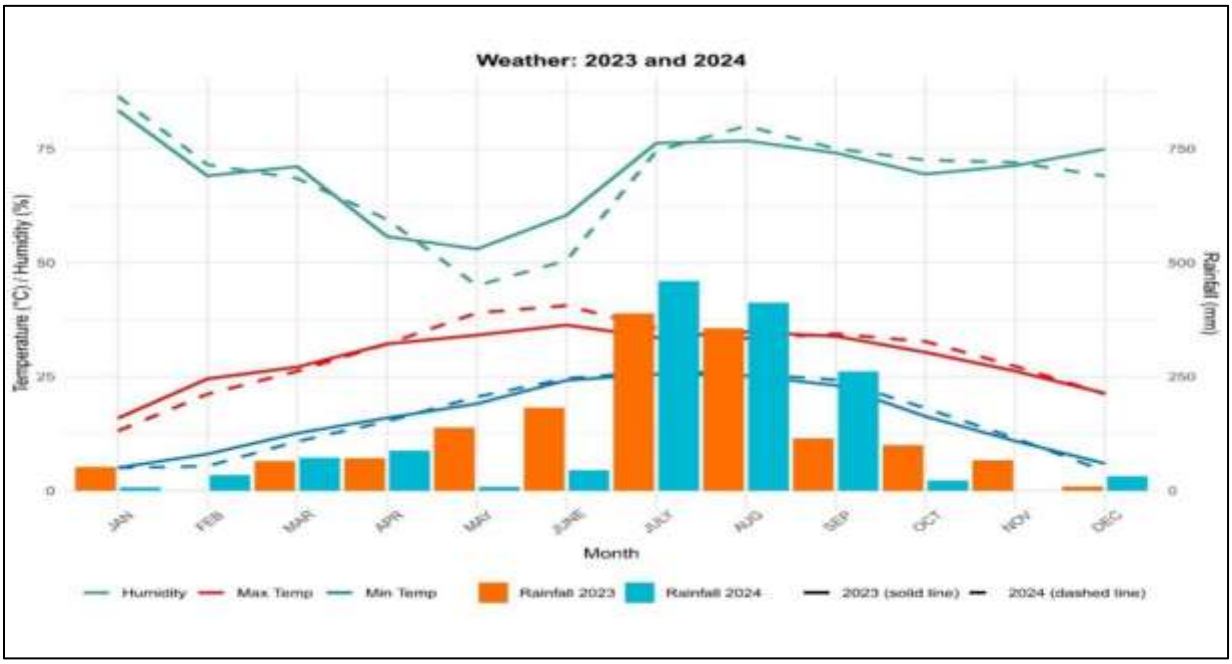

Fig. 2: Graphical illustration of monthly average weather at experimental site

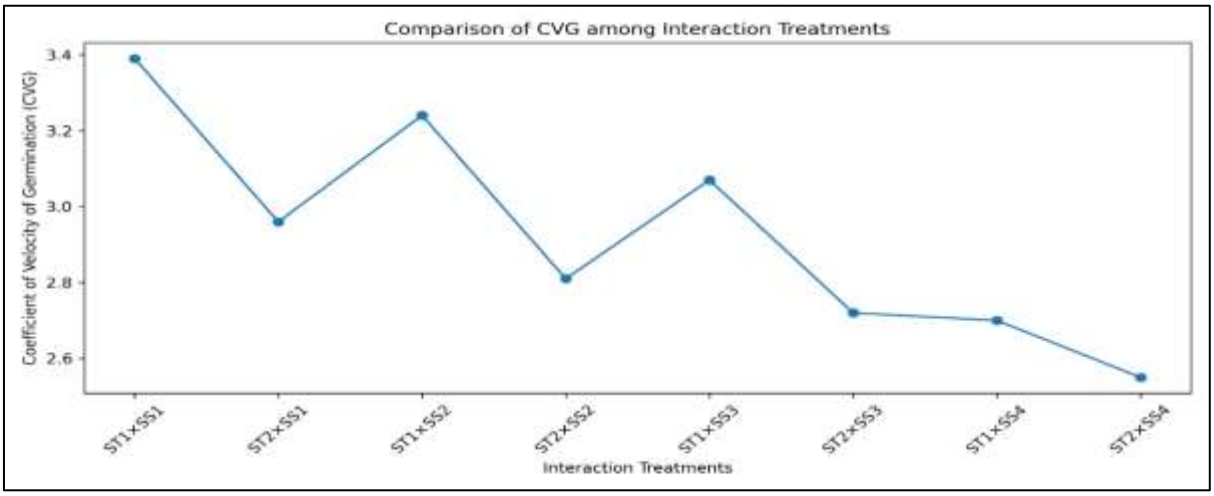

Fig. 3: Effect of seed source × sowing season interaction on coefficient of velocity of germination (CVG) of *Santalum album* L.

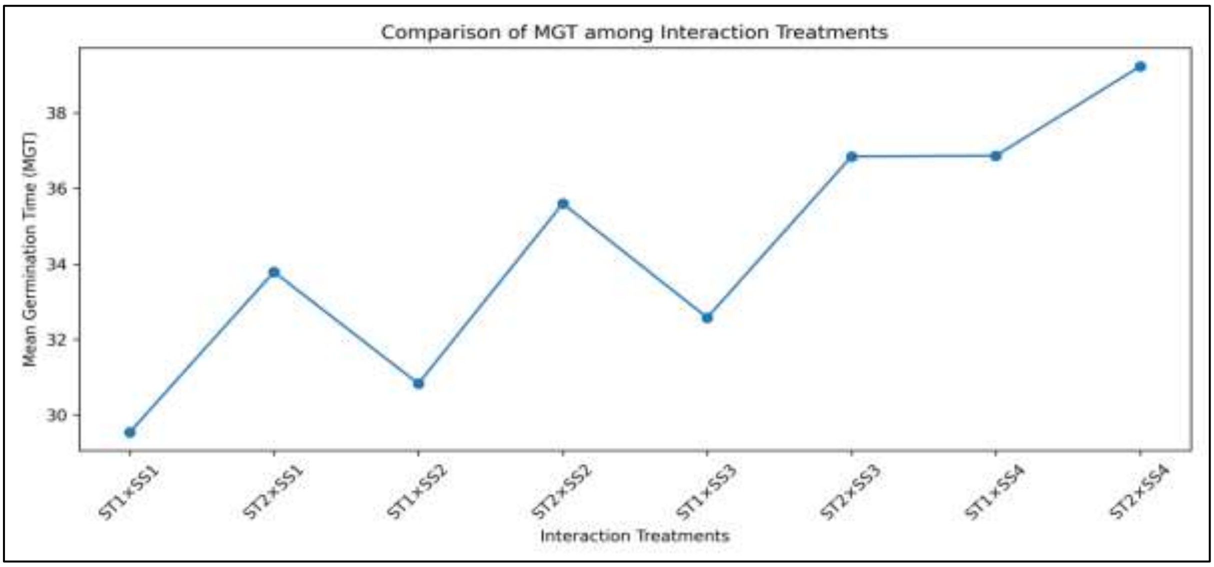

Fig. 4: Effect of seed source × sowing season interaction on mean germination time (MGT) of *Santalum album* L.

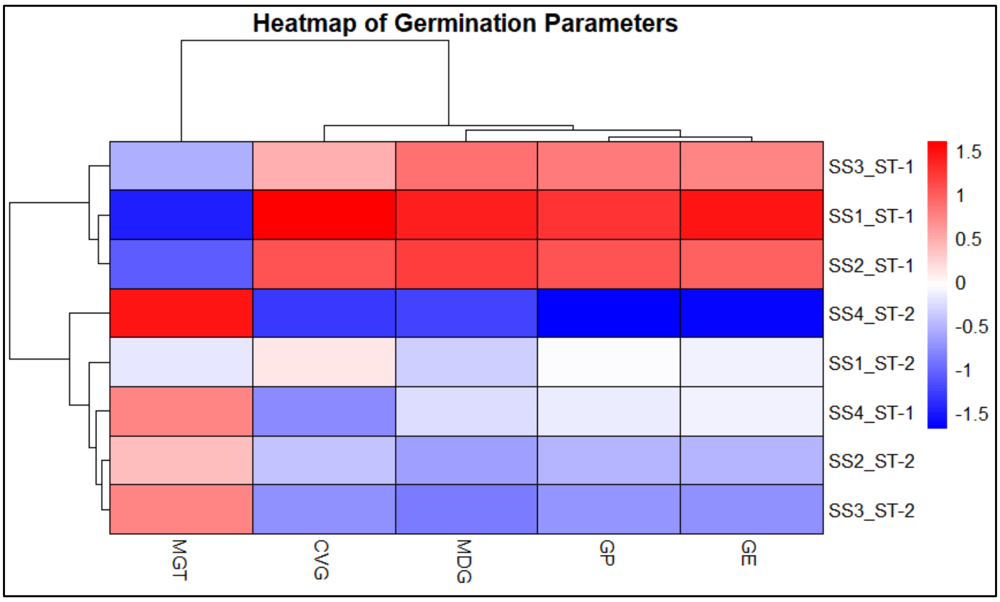

Fig. 5: Heat map and hierarchical cluster analysis of germination parameters (GP, GE, CVG, MDG and MGT) among different seed source × sowing season combinations of sandalwood (*Santalum album* L.)

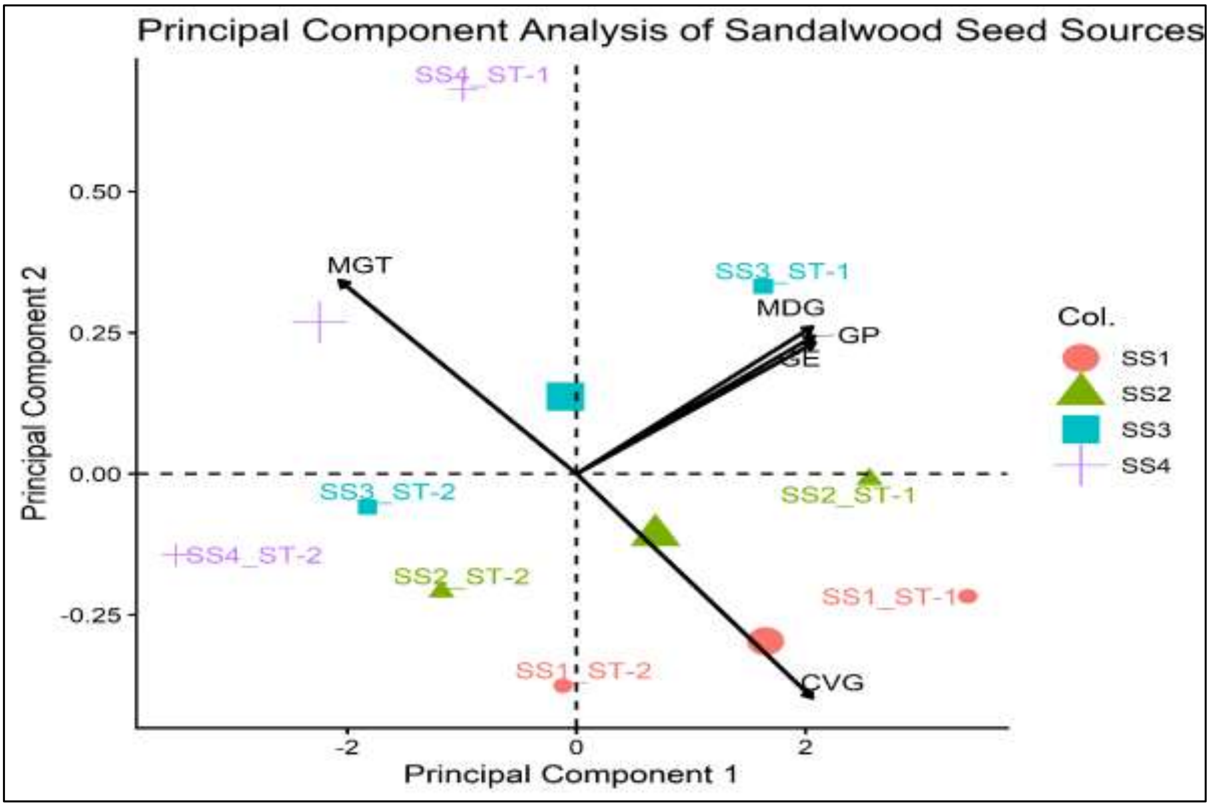

Fig. 6: Principal component analysis (PCA) biplot depicting the association between seed sources, sowing seasons, and germination traits of sandalwood (*Santalum album* L.) under Jammu subtropical conditions

Table 1: Treatment combinations

Treatments	Seed sources (SS)	Sowing season (ST)
T1	Mysore (Karnataka) (SS1)	Spring season (ST-1)
T2	Mysore (Karnataka) (SS1)	Rainy season (ST-2)
T3	Coimbatore (Tamil Nadu) (SS2)	Spring season (ST-1)
T4	Coimbatore (Tamil Nadu) (SS2)	Rainy season (ST-2)
T5	Idukki (Kerala) (SS3)	Spring season (ST-1)
T6	Idukki (Kerala) (SS3)	Rainy season (ST-2)
T7	Hamirpur (Himachal Pradesh) (SS4)	Spring season (ST-1)
T8	Hamirpur (Himachal Pradesh) (SS4)	Rainy season (ST-2)

Table 2: Effect of different seed sources and sowing season on the germinability of sandalwood (*Santalum album* L.) during 2023-2025

Factors	Levels / Treatments	Germination percentage (%)	Germinative energy (%)	Coefficient of velocity of germination	Mean daily germination	Mean germination time
Sowing season (ST)	ST-1	46.85a	21.35a	3.10a	0.52a	32.46b
	ST-2	34.75b	14.80b	2.76b	0.40b	36.37a
	CD (0.05)	2.18	1.19	0.05	0.02	0.59
	SE(m) ±	0.75	0.41	0.02	0.01	0.20
Seed sources (SS)	SS1	45.70a	21.00a	3.18a	0.50a	31.67d
	SS2	43.10ab	19.00b	3.02b	0.48ab	33.21c
	SS3	41.20b	18.00bc	2.89c	0.46b	34.72b
	SS4	33.20c	14.30c	2.62d	0.40c	38.06a
	CD (0.05)	3.09	1.69	0.07	0.03	0.53
	SE(m) ±	1.07	0.58	0.03	0.01	0.29
Interaction (ST × SS)	ST1× SS1	51.00	24.40	3.39a	0.57	29.54g
	ST2 × SS1	40.40	17.60	2.96d	0.43	33.79d
	ST1 × SS2	49.60	22.20	3.24b	0.55	30.83f
	ST2 × SS2	36.60	15.80	2.81e	0.41	35.60c
	ST1 × SS3	47.40	21.20	3.07c	0.53	32.58e
	ST2 × SS3	35.00	14.80	2.72ef	0.39	36.85c
	ST1 × SS4	39.40	17.60	2.70f	0.44	36.87b
	ST2 × SS4	27.00	11.00	2.55g	0.36	39.24a
	CD (0.05)	NS	NS	0.11	NS	1.18
	SE(m) ±	1.51	0.83	0.04	0.02	0.41
NS- Non significant						
ST			SS			
Sowing time			Seed sources			
ST-1	ST-2		SS1	SS2	SS3	SS4
(Spring season)	(Rainy season)		Mysore (Karnataka) seeds	Coimbatore (Tamil Nadu) seeds	Idukki (Kerala) seeds	Hamirpur (Himachal Pradesh) seeds