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**Statistical Assessment of the Superiority of Agro-Climatic Zones for Sandalwood
(*Santalum album* L.) Cultivation Based on Variability in Tree Growth and Soil Fertility
Parameters in Karnataka, India**

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ABSTRACT

Sandalwood (*Santalum album* L.), a highly valued aromatic tree species, is renowned for its heartwood, which is rich in essential oils used in perfumes, cosmetics, and traditional medicine. In India, Karnataka is a major hub for sandalwood cultivation, owing to its diverse agro-climatic conditions and historical significance in sandalwood trade. This study aimed to statistically evaluate the suitability of nine Agro-Climatic Zones (ACZs) for optimal sandalwood cultivation by analyzing variability in soil fertility and tree growth parameters across 73 taluks. Data were collected on key soil properties—pH, electrical conductivity (EC), organic carbon, macro- and micronutrients—as well as tree parameters such as age, height, diameter, heartwood content, and heartwood diameter. Rainfall across taluks ranged from 266.5 to 1376.4 mm (mean: 471 mm, CV: 56.9%), and mean annual temperatures varied between 23.7°C and 28.0°C (mean: 25.2°C, CV: 4.4%). Tree ages ranged from 9.5 to 11.5 years across zones. Soil pH varied from 6.53 to 7.31, while EC ranged from 0.06 to 0.39 dS/m. Substantial variability was observed in nutrient concentrations: nitrogen (127.35–402.77 kg/ha), phosphorus (18.68–39.20 kg/ha), potassium (300.4–661.08 kg/ha), calcium (1428.38–8078.47 ppm), and micronutrients including Fe, Mn, Zn, and Cu. Statistical comparisons (Student's *t*-test) revealed significant differences in tree diameter, heartwood diameter, and heartwood percentage among specific ACZs. No significant variation was observed in tree height. Ranking of zones based on tree performance (RS1), soil pH and EC (RS2), macro-nutrients (RS3), and micro-nutrients (RS4) indicated that ACZ-3 ranked highest overall (rank sum: 69), followed by ACZ-8 (rank sum: 75). Notably, ACZ-6 and ACZ-9 also demonstrated superior performance for selected parameters. These findings underscore the influence of soil fertility and agro-climatic conditions on sandalwood growth and heartwood formation. The results are valuable for identifying site-specific strategies for sandalwood plantation development and improving heartwood yield under similar environmental

conditions. These findings highlight ACZ-3 and ACZ-8 as optimal for sandalwood cultivation, with ACZ-6 excelling in heartwood production, guiding zone-specific management for maximizing growth and heartwood yield.

Key words: *Santalum album*, agro-climatic zones, soil fertility, heartwood, tree growth, site suitability

INTRODUCTION

Indian sandalwood (*Santalum album* L.) is considered as the most valuable and precious tree among 17 species of the genus *Santalum*. Apart from African blackwood (*Dalbergia melanoxylon*), agarwood (*Aquilaria malaccensis*), red sanders (*Pterocarpus santalinus*) and ebony (*Diospyros ebenum*), sandalwood is one of the costliest tree species. *Santalum* species have been woven into people's tradition, culture, heritage and religious values from cradle to death. Sandalwood (*Santalum album* L.) is a highly valued tropical tree species native to southern India, prized for its aromatic heartwood and essential oil. It holds immense commercial, medicinal, and cultural importance, making it a key species for plantation forestry in peninsular India. Karnataka, being one of the traditional strongholds of natural sandalwood distribution, offers a wide range of agro-climatic conditions that influence its growth and heartwood development. The growth and quality of sandalwood, particularly its heartwood content and diameter, are influenced by a complex interplay of soil fertility, climatic factors, and management practices. Understanding these factors is critical for optimizing cultivation and ensuring sustainable production, especially given the species' economic importance and declining natural populations due to overexploitation.

Successful cultivation of sandalwood depends not only on genetic factors but also on the suitability of environmental conditions, particularly soil fertility and climatic parameters such as temperature and rainfall. Despite the growing demand for sandalwood and its economic potential, there exists limited scientific assessment of how agro-climatic variability within Karnataka affects its growth performance, heartwood formation, and yield.

Karnataka encompasses nine Agro-Climatic Zones (ACZs), each characterized by distinct rainfall, temperature, and soil properties, offering a unique opportunity to study sandalwood's adaptability across varied environments. Previous research has highlighted the role of soil parameters such as pH, electrical conductivity (EC), organic carbon (OC), and macro- and micronutrients in influencing tree growth and heartwood formation. However, comprehensive

studies assessing the variability of these parameters and their impact on sandalwood across multiple ACZs in Karnataka are limited. Understanding the relationship between these agro-ecological differences and sandalwood performance is critical for selecting optimal sites for cultivation, improving productivity, and guiding reforestation or agroforestry initiatives.

The present study aims to evaluate the performance of sandalwood plantations across nine major ACZs in Karnataka by analyzing tree growth metrics such as height, diameter, heartwood percentage, and heartwood diameter alongside comprehensive soil fertility data. By employing statistical tools (Student's t-test and ranking based on rank sums) to assess inter-zonal variability and significance, the study seeks to identify the most suitable zones for maximizing heartwood yield and overall tree performance. The findings are expected to serve as a scientific basis for the selection of suitable plantation sites and the development of management strategies tailored to region-specific soil and climatic conditions. They will also guide farmers, policymakers, and researchers in enhancing sandalwood production across diverse agro-climatic zones of Karnataka.

MATERIALS AND METHODS

Data for this study were collected from 73 farm-grown sandalwood (*Santalum album L.*) plantations located across various districts in Karnataka, India, managed by individual farmers. The geographical coordinates of the study sites spanned latitudes from 12.16° to 17.57° N and longitudes from 74.56° to 78.13° E. These sites are characterized by a wide range of climatic conditions, with mean annual temperatures ranging from 29°C to 35°C and annual rainfall varying between 309 mm and 1915 mm. The selected plantations represented diverse agro-climatic zones of Karnataka and included trees of varying ages. A total of 73 field plots (as detailed in Tables 1) were established on farmers' lands. Plot sizes varied from 110 m² to 533 m², adjusted based on tree density to ensure the inclusion of at least 25 to 30 sandalwood trees per plot for meaningful assessment. Tree age was determined based on the planting year, as reported by the respective farmers.

A total of seventy-three sample plots were established across various districts of Karnataka to represent diverse agro-climatic conditions and management practices. The distribution of plots was as follows: Bangalore Rural (5), Tumakuru (4), Chikkaballapur (7), Chitradurga (8), Kolar (11), Koppal and Kustagi (7), Belagavi (4), Chikkamagaluru (5), Shivamogga (3), Hassan (2), Davangere (2), Haveri (2), Udupi (2), Ballari (1), Bagalkot (2),

Raichur (2), Gadag (1), Mandya (1), Mysuru (1), and Ramanagara (3). These locations were selected to capture the variability in edaphic and climatic conditions affecting sandalwood growth across the state.

Table 1 Distribution of sample plots as per Agro-Climatic Zones (ACZ)

Agro-Climatic Zones (ACZ)	<u>Districts/places</u>	Plots
ACZ 2 – North Eastern Dry Zone	Raichur, Gulbarga	2
ACZ 3 – Northern Dry Zone	Bagalkote, Belgum, Bellary, Bijapura, Dharwad, Koppal	15
ACZ 4 – Central Dry Zone	Challakere, Chitradurga, Davanagere, Harihara, Hiriya, Hosadurga, Holalkere, Jagalur, Molkalmuru, Kadur, Madhugiri, Pavagada, C. N. Halli, Sira	13
ACZ 5 – Eastern Dry Zone	Gubbi, Tumakuru, Anekal, Bengaluru South, Bengaluru North, Channapatna, Devanahalli, Doddabalapur, Hoskote, Koratagere, Kanakapura, Magadi, Nelmangala, Ramanagara, Bagepalli, Bangarpet, Chikkabalapur, Chintamani, Gudibanda, Gouribidnur, Kolar, Malur, Mulbagal, Shidlaghatta, Srinivasapura	27
ACZ 6 – Southern Transition Zone	Hunsur, Heggada Devana Kote, Periyapatna, Hole Narasipura, Alur, Arkalgud, Belur, Tarikere, Bhadravathi, Shivamogga, Honnali, Shikaripura, Channagiri.	8
ACZ 7 – Southern Dry Zone	Krishnaraja Nagar, T. Narasipur, Mysuru, Kollegal, Nanjangud, Turuvekere, Kunigal, Nagamangala, Srirangapatna, Arasikere, Malavally, Maddur, Mandya, Pandavapura, Krishnarajapet, Channarayapatna, Hassan, Chamarajanagara, Yelandur, Gundlupet and Tiptur	2
ACZ 8 – Northern Transition Zone	Haveri	2
ACZ 9 – Hill Zone	Kodagu, Shimoga, Uttara Kannada	2
ACZ 10 – Coastal Zone	Dakshina Kannada, Udupi	2
Total		73

Field observations were recorded for tree height and girth/diameter at breast height (DBH) using measuring tape, heartwood diameter was recorded using ERT, and heartwood content was calculated across all 73 selected sandalwood plantations. Soil samples were collected using the V-shaped method from the topsoil up to a depth of 50 cm. These samples were analyzed for soil pH, electrical conductivity (EC), organic carbon (OC %), and macro- (N, P, K, Ca, Mg) and micronutrient (Fe, S, Zn, Mn, Cu) contents at the Krishi Vigyan Kendra (KVK), Hirehalli.

Traditional methods for evaluating heartwood content often involve destructive sampling, which is impractical for high-value or protected species like sandalwood. To address this challenge, Electrical Resistance Tomography (ERT) has emerged as a non-destructive, species-specific imaging technique capable of assessing the internal structure of living trees, including heartwood and sapwood proportions, internal decay, and hollowness.

To assess heartwood formation and quantify heartwood content in standing sandalwood (*Santalum album* L.) trees, Electrical Resistance Tomography (ERT) was employed as a non-destructive diagnostic tool. ERT is an advanced imaging technique that evaluates the internal structure of tree stems by measuring the electrical resistivity distribution using electrodes placed circumferentially around the trunk. In sandalwood, this method is particularly valuable due to the high commercial importance of heartwood and the necessity to preserve standing trees during assessment. Heartwood and sapwood differ in moisture content, electrolyte concentration, and chemical composition, which directly influences their electrical resistivity. Typically, regions with low electrical resistance (ER) correspond to areas with higher moisture and ionic content (e.g., sapwood), while high ER zones often indicate drier, denser regions such as heartwood. By mapping these resistivity variations, ERT allows precise visualization of internal zones, including heartwood, sapwood, decay pockets, and potential mechanical defects.

The ERT setup involves inserting shallow electrodes (often nails) at standardized positions around the tree stem. These electrodes access deeper wood sections while causing minimal injury to the tree. The method's high spatial resolution enables accurate differentiation of internal zones, making it ideal for heartwood quantification in living trees without the need for coring or destructive sampling.

The use of ERT in tropical tree species, particularly in Indian sandalwood, has been pioneered by the Institute of Wood Science and Technology (IWST). ERT has shown significant promise in estimating heartwood and sapwood proportions, detecting internal decay, and identifying hollowness in valuable timber trees. Given the species-specific nature of wood anatomy, ion distribution, and moisture retention, ERT generates unique resistivity profiles for each species. This allows for detailed tomographic reconstruction tailored to the physiological characteristics of *Santalum album*, thereby enhancing the accuracy of heartwood estimation.

The descriptive statistics viz., minimum, maximum, mean, standard deviation and coefficient of variation (%) were derived for each parameter observed in the sandalwood study under different

zones. The study was conducted with the objective of assessing the variability in the soil and plant parameters as discussed by Gomez and Gomez (1985). The differences between mean values of tree parameters observed under each pair of ACZs could be tested based on the Student's t-test for any significant difference in the performance of trees (Gomez and Gomez, 1984). The t-test could be given as

$$t = \frac{(\bar{x}_1 - \bar{x}_2)}{\sqrt{\left(\frac{s_p^2}{n_1} + \frac{s_p^2}{n_2}\right)}} \quad \text{Where} \quad s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}$$

In the two ACZs to be compared, s_1^2 is the standard deviation of locations in the 1st ACZ; s_2^2 is the standard deviation of locations in the 2nd ACZ; n_1 and n_2 are the number of locations in the 1st and 2nd ACZs respectively. The standard error (SE) of the difference between means of two ACZs could be given as

$$SE(\bar{x}_1 - \bar{x}_2) = \sqrt{\left(\frac{s_p^2}{n_1} + \frac{s_p^2}{n_2}\right)}$$

In order to assess the superiority of ACZs for growing sandalwood cultivation, ranks were assigned to the mean values of different parameters observed under ACZs under 4 categories viz., (i) heartwood, heartwood diameter, tree height and tree diameter; (ii) soil pH and electrical conductivity; (iii) soil macro-nutrient parameters of organic carbon, N, P and K; and (iv) soil micro-nutrient parameters of calcium, magnesium, sulphur, iron, manganese, zinc and copper. Based on the ranks assigned to the parameters, rank sums were derived under each category and the over-all rank sum was derived for each ACZ. The ACZ with lowest rank sum could be identified as superior, followed by other ACZs in the order of rank sums derived based on the magnitude of soil and tree parameters.

RESULTS AND DISCUSSION

Distribution of rainfall and temperature under different ACZs

Rainfall across the Agro-Climatic Zones (ACZs) showed considerable variation, ranging from a minimum of 266.5 mm in ACZ-3 to a maximum of 1376.4 mm in ACZ-10. The mean annual rainfall varied from 324.2 mm in ACZ-2 to 1376.4 mm in ACZ-10, with an overall mean of 599.2 mm and a coefficient of variation (CV) of 66.8%. The CV for rainfall across zones was highly variable, from as low as 1.1% in ACZ-2 to as high as 54.9% in ACZ-5, with an overall mean CV of 22.7%. Temperature variations among the ACZs were relatively moderate, ranging

from 23.7°C in ACZ-5 to 28.0°C in ACZ-2. The mean temperature across zones varied from 24.3°C in ACZ-5 to 27.4°C in ACZ-2, with an overall mean of 25.8°C and a CV of 4.1%. The temperature CV was narrow, ranging from 1.5% in ACZ-7 to 4.8% in ACZ-3, with an overall mean CV of 1.5% (Table 2).

Table 2. ACZ-wise descriptive statistics of rainfall and temperature observed during 2010 to 2022

ACZ	Locations	Rainfall (mm)					Temperature (°C)				
		Minimum	Maximum	Mean	SD	CV (%)	Minimum	Maximum	Mean	SD	CV (%)
2	2	321.6	326.7	324.2	3.6	1.1	26.7	28.0	27.4	0.9	3.3
3	15	266.5	608.9	376.6	146.8	39.0	23.9	26.9	25.8	1.2	4.8
4	13	316.4	647.1	398.9	86.9	21.8	24.5	26.9	25.6	0.5	2.1
5	27	346.1	1170.5	467.8	256.6	54.9	23.7	25.6	24.3	0.4	1.8
6	8	392.0	515.1	434.6	53.8	12.4	24.3	26.9	25.4	0.9	3.6
7	2	1161.3	1276.4	1218.9	81.4	6.7	24.4	24.9	24.7	0.4	1.5
8	2	355.5	355.5	355.5	0.0	0.0	25.4	25.4	25.4	0.0	0.0
9	2	439.8	439.8	439.8	0.0	0.0	26.4	26.4	26.4	0.0	0.0
10	2	1376.4	1376.4	1376.4	0.0	0.0	27.2	27.2	27.2	0.0	0.0
<i>Pooled</i>	73	266.5	1376.4	470.8	268.0	56.9	23.7	28.0	25.8	1.1	4.1
<i>Mean</i>	8.1			599.2		22.7			25.8		2.9
<i>SD</i>	8.8			400.4					1.1		
<i>CV (%)</i>	108.1			66.8					4.1		

Descriptive statistics of soil and tree parameters under ACZ-2

The descriptive statistics of soil properties and sandalwood tree parameters under Agro-Climatic Zone 2 (ACZ-2) are presented in Table 4. The data were collected from two locations, each consisting of 25 sandalwood trees aged approximately seven years. Soil pH ranged from 7.01 to 8.2, with a mean of 7.61 and a coefficient of variation (CV) of 11.1%, indicating slightly alkaline conditions. Electrical conductivity (EC) varied between 0.38 to 0.49 dS m⁻¹, with a mean of 0.44 dS m⁻¹ (CV: 17.9%), reflecting moderate salinity levels.

Soil organic carbon content ranged from 0.93% to 1.15%, with a mean of 1.04% (CV: 15.0%). Available nitrogen (N) levels ranged from 337.4 to 417.3 kg/ha, averaging 377.35 kg/ha (CV: 15.0%). Available phosphorus (P) ranged from 31.46 to 39.0 kg/ha, with a mean of 35.23 kg/ha (CV: 15.1%), while available potassium (K) showed a wide variation, ranging from 154 to 350 kg/ha, with a mean of 252 kg/ha (CV: 55.0%). Calcium (Ca) levels in the soil varied between 3684.5 and 5495.0 ppm, with a mean of 4589.7 ppm (CV: 27.9%), and magnesium (Mg) ranged from 582 to 735 ppm, averaging 658.5 ppm (CV: 16.4%). Soil sulphur (S) was relatively uniform, ranging from 186.8 to 196.56 ppm, with a mean of 191.68 ppm (CV: 3.6%).

Among the micronutrients, iron (Fe) levels varied widely from 4.15 to 9.8 ppm, with a mean of 6.98 ppm (CV: 57.3%). Manganese (Mn) ranged from 1.35 to 3.0 ppm (mean: 2.18 ppm, CV: 53.6%), zinc (Zn) from 1.6 to 1.8 ppm (mean: 1.7 ppm, CV: 8.3%), and copper (Cu) from 0.6 to 0.8 ppm (mean: 0.7 ppm, CV: 20.2%).

Regarding tree growth, tree height ranged from 5.92 to 6.72 meters, with a mean of 6.32 m (CV: 9.0%), and diameter at breast height (DBH) ranged from 8.41 to 8.84 cm, with a mean of 8.62 cm (CV: 3.6%). The heartwood diameter varied from 3.78 to 3.99 cm (mean: 3.89 cm, CV: 3.8%), and the heartwood percentage ranged from 20.49% to 20.97%, averaging 20.73% with a narrow CV of 1.6%.

Descriptive statistics of soil and tree parameters under ACZ-3

The descriptive statistics of soil properties and sandalwood tree parameters under Agro-Climatic Zone 3 (ACZ-3), based on data collected from 15 locations, are presented in Table 3. The number of trees assessed at each location ranged from 10 to 27, with a mean of 22 trees (CV: 26.7%). The age of the trees varied considerably, ranging from 6 to 17 years, with a mean age of 10.9 years (CV: 25.5%).

Soil pH showed a wide range from 5.52 to 8.72, with a mean of 7.19 and a coefficient of variation (CV) of 13.4%, indicating the presence of both slightly acidic and alkaline soils. Electrical conductivity (EC) varied between 0.19 and 0.61 dS m⁻¹, with a mean of 0.30 dS m⁻¹ (CV: 42.5%), suggesting moderate variability in soil salinity across sites. Soil organic carbon content was highly variable, ranging from 0.09% to 1.87%, with a mean of 0.51% (CV: 99.2%). Available nitrogen (N) ranged from 32.6 to 678.5 kg/ha, with a mean of 163.99 kg/ha (CV: 103.9%), reflecting substantial spatial variation. Available phosphorus (P) varied from 8.45 to 57.13 kg/ha (mean: 33.91 kg/ha, CV: 55.2%), and available potassium (K) ranged from 140 to 1344 kg/ha, with a mean of 463.07 kg/ha (CV: 78.5%). Soil calcium (Ca) exhibited a broad range from 1920 to 24,115 ppm, with a mean of 8078.47 ppm (CV: 73.2%), while magnesium (Mg) ranged from 79 to 812 ppm, averaging 559.05 ppm (CV: 38.1%). Soil sulphur (S) content varied from 4.56 to 210 ppm, with a mean of 103.11 ppm (CV: 91.6%), reflecting high heterogeneity. Among micronutrients, iron (Fe) levels ranged from 3.9 to 38.1 ppm (mean: 9.97 ppm, CV: 86.9%), manganese (Mn) from 0.12 to 4.45 ppm (mean: 1.34 ppm, CV: 86.0%), zinc (Zn) from 0.17 to 5.10 ppm (mean: 1.49 ppm, CV: 90.3%), and copper (Cu) from 0.45 to 3.00 ppm (mean: 1.53 ppm, CV: 51.0%).

Regarding tree growth parameters, tree height ranged from 3.90 to 14.42 meters, with a mean height of 8.75 m (CV: 40.3%), and diameter at breast height (DBH) varied from 8.01 to 13.44 cm, with a mean of 10.37 cm (CV: 11.8%). The heartwood diameter ranged from 4.23 to 6.50 cm (mean: 5.35 cm, CV: 10.9%), while heartwood percentage varied from 22.49% to 31.09%, with a mean of 27.22% (CV: 9.6%).

Descriptive statistics of soil and tree parameters under ACZ-4

The descriptive statistics of soil properties and sandalwood tree characteristics under Agro-Climatic Zone 4 (ACZ-4), based on observations from 13 locations, are presented in Table 3. The number of sandalwood trees per location ranged from 10 to 30, with a mean of 23.46 (CV: 20.2 %). The age of the trees varied from 5 to 17 years, with a mean age of 9.5 years (CV: 36.0 %), indicating diverse plantation ages across the zone.

Soil pH was relatively stable, ranging from 6.43 to 7.50, with a mean of 7.04 and a coefficient of variation (CV) of 4.6 %, suggesting near-neutral conditions. Electrical conductivity (EC) ranged from 0.07 to 0.28 dS m⁻¹, with a mean of 0.15 dS m⁻¹ (CV: 37.9%), indicating generally low salinity levels. Soil organic carbon ranged from 0.02 % to 1.07 %, with a mean of 0.36 % (CV: 94.6 %), reflecting considerable variation in soil organic matter. Available nitrogen (N) content ranged from 7.25 to 388.2 kg/ha, averaging 127.35 kg/ha (CV: 90.4 %). Available phosphorus (P) levels were highly variable, ranging from 2.14 to 145 kg/ha, with a mean of 37.98 kg/ha (CV: 102.0 %), while available potassium (K) ranged from 210 to 1400 kg/ha, with a mean of 661.08 kg/ha (CV: 68.2 %). Soil calcium (Ca) ranged from 903 to 3719 ppm, with a mean of 1784.46 ppm (CV: 39.8 %), and magnesium (Mg) varied widely from 148 to 1471 ppm, averaging 611.92 ppm (CV: 73.6 %). Soil sulphur (S) levels ranged from 0.93 to 120.96 ppm, with a mean of 21.29 ppm (CV: 151.0 %), indicating high variability. Among micronutrients, iron (Fe) ranged from 3.12 to 46.8 ppm (mean: 14.18 ppm, CV: 106.1 %), manganese (Mn) from 0.95 to 14.0 ppm (mean: 3.46 ppm, CV: 107.1%), zinc (Zn) from 0.05 to 3.76 ppm (mean: 0.88 ppm, CV: 119.5 %), and copper (Cu) from 0.10 to 5.15 ppm, with a mean of 1.94 ppm (CV: 85.6 %), all of which showed substantial spatial variability.

In terms of tree growth parameters, tree height ranged from 3.08 to 12.95 meters, with a mean of 9.36 m (CV: 29.3%), and diameter at breast height (DBH) varied from 7.95 to 12.01 cm, averaging 9.32 cm (CV: 13.2%). The heartwood diameter ranged from 2.25 to 6.51 cm, with a mean of 4.62 cm (CV: 24.0%), while the heartwood percentage varied from 7.77% to 35.49%,

with a mean of 25.09% (CV: 25.5%), reflecting differences in tree maturity and site conditions.

Descriptive statistics of soil and tree parameters under ACZ-5

The descriptive statistics of soil properties and sandalwood tree characteristics under Agro-Climatic Zone 5 (ACZ-5), based on data from 27 locations, are presented in Table 3. The number of sandalwood trees per location ranged from 10 to 29, with a mean of 21.74 (CV: 25.1 %). Tree age ranged from 6 to 13 years, averaging 9.6 years (CV: 21.1 %), reflecting moderately uniform stand maturity.

Soil pH ranged from 5.55 to 8.4, with a mean of 6.87 and a coefficient of variation (CV) of 8.7 %, indicating a mix of slightly acidic to alkaline soils. Electrical conductivity (EC) ranged from 0.08 to 0.36 dS m⁻¹, with a mean of 0.14 dS m⁻¹ (CV: 40.9 %), indicating generally low to moderate salinity. Soil organic carbon ranged widely from 0.02 % to 1.36 %, with a mean of 0.53 % (CV: 74.5 %). Available nitrogen (N) ranged from 10.5 to 493.5 kg/ha, with a mean of 185.13 kg/ha (CV: 78.1 %). Available phosphorus (P) varied from 0.42 to 87.3 kg/ha, averaging 27.92 kg/ha (CV: 89.7 %), while available potassium (K) ranged from 194 to 1260 kg/ha, with a mean of 455.96 kg/ha (CV: 60.3 %). Calcium (Ca) levels ranged from 400 to 5275 ppm, with a mean of 2185.33 ppm (CV: 65.6 %), and magnesium (Mg) ranged from 108.0 to 745.5 ppm, averaging 309.06 ppm (CV: 53.8 %). Soil sulphur (S) content ranged from 0.62 to 195.93 ppm, with a mean of 31.5 ppm (CV: 181.7 %), indicating extremely high variability across the zone. Micronutrient concentrations were also highly variable: iron (Fe) ranged from 1.8 to 23.6 ppm (mean: 11.74 ppm, CV: 66.3 %), manganese (Mn) from 0.17 to 8.7 ppm (mean: 2.12 ppm, CV: 82.3 %), zinc (Zn) from 0.03 to 9.87 ppm (mean: 0.77 ppm, CV: 244.7 %), and copper (Cu) from 0.10 to 8.12 ppm (mean: 1.96 ppm, CV: 84.8 %).

In terms of tree growth characteristics, tree height varied from 3.89 to 15.29 meters, with a mean height of 8.17 m (CV: 40.5 %), while diameter at breast height (DBH) ranged from 6.51 to 11.17 cm, with a mean of 8.85 cm (CV: 13.7 %). Heartwood diameter ranged from 2.61 to 6.13 cm, with a mean of 4.4 cm (CV: 18.2 %), and heartwood percentage ranged from 12.25 % to 32.57 %, averaging 25.24 % (CV: 18.9 %), reflecting good potential for economic returns under this Agro-Climatic Zone.

Descriptive statistics of soil and tree parameters under ACZ-6

The descriptive statistics of soil characteristics and sandalwood tree parameters under Agro-Climatic Zone 6 (ACZ-6), based on data from 8 locations, are presented in Table 3. The

number of trees per location ranged from 12 to 25, with a mean of 20.75 (CV: 21.5 %). Tree age varied between 8 to 17 years, with a mean of 11.5 years (CV: 26.7 %).

Table 3. Descriptive statistics of soil and tree parameters in ACZ-3, 4, 5, 6

Parameter	ACZ-3 (15)		ACZ-4 (13)		ACZ-5 (27)		ACZ-6 (8)	
	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
pH	7.19	13.4	7.04	4.6	6.87	8.7	6.53	5.8
EC	0.30	42.5	0.15	37.9	0.14	40.9	0.06	50.2
OC	0.51	99.2	0.36	94.6	0.53	74.5	0.59	32.8
N	163.99	103.9	127.35	90.4	185.13	78.1	214.08	32.7
P	33.91	55.2	37.98	102.0	27.92	89.7	18.68	67.0
K	463.07	78.5	661.08	68.2	455.96	60.3	334.25	46.1
Ca	8078.47	73.2	1784.46	39.8	2185.33	65.6	1428.38	60.3
Mg	559.05	38.1	611.92	73.6	309.06	53.8	371.68	68.8
S	103.11	88.8	21.29	151.0	31.50	181.7	45.11	95.7
Fe	9.97	86.9	14.18	106.1	11.74	66.3	4.94	62.1
Mn	1.34	86.0	3.46	107.1	2.12	82.3	1.65	93.4
Zn	1.49	90.3	0.88	119.5	0.77	244.7	0.72	89.0
Cu	1.53	51.0	1.94	85.6	1.96	84.8	0.23	78.6
Trees	22.00	26.7	23.46	20.2	21.74	25.1	20.75	21.5
TA	10.93	25.5	9.46	36.0	9.59	21.1	11.50	26.7
TH	8.75	40.3	9.36	29.3	8.17	40.5	10.34	8.3
TD	10.37	11.8	9.32	13.2	8.85	13.7	10.09	25.4
HWD	5.35	10.9	4.62	24.0	4.40	18.2	5.23	24.3
HW	27.22	9.6	25.09	25.5	25.24	18.9	27.66	7.5

Soil pH ranged from 6.26 to 7.39, with a mean of 6.53 and a coefficient of variation (CV) of 5.8 %, indicating slightly acidic to neutral soil conditions. Electrical conductivity (EC) was relatively low, ranging from 0.02 to 0.09 dS m⁻¹, with a mean of 0.06 dS m⁻¹ (CV: 50.2 %), suggesting very low salinity with moderate variability. Soil organic carbon (OC) ranged from 0.29 % to 0.86 %, with a mean of 0.59 % (CV: 32.8 %). Available nitrogen (N) varied from 105.23 to 312.07 kg/ha, with a mean of 214.08 kg/ha (CV: 32.7 %). Available phosphorus (P) ranged from 5.15 to 44.92 kg/ha, with a mean of 18.68 kg/ha (CV: 67.0 %), while available potassium (K) ranged from 210 to 686 kg/ha, averaging 334.25 kg/ha (CV: 46.1 %). Calcium (Ca) content ranged from 333 to 2872 ppm, with a mean of 1428.38 ppm (CV: 60.3 %), while magnesium (Mg) ranged from 52.5 to 742.5 ppm, averaging 371.68 ppm (CV: 68.8 %). Soil sulphur (S) ranged from 11.87 to 127.18 ppm, with a mean of 45.11 ppm (CV: 95.7 %), indicating considerable variability. Micronutrient levels showed high variability as well: iron (Fe) ranged from 0.12 to 8.07 ppm (mean: 4.94 ppm, CV: 62.1 %), manganese (Mn) from 0.3 to 4.8 ppm (mean: 1.65 ppm, CV: 93.4 %), zinc (Zn) from 0.12 to 1.85 ppm (mean: 0.72 ppm, CV:

89.0 %), and copper (Cu) from 0.07 to 0.6 ppm (mean: 0.23 ppm, CV: 78.6 %).

In terms of tree growth parameters, tree height ranged from 8.86 to 11.76 meters, with a mean height of 10.34 m (CV: 8.3 %), and diameter at breast height (DBH) ranged from 7.08 to 15.02 cm, with a mean of 10.09 cm (CV: 25.4 %). The heartwood diameter ranged from 3.86 to 7.67 cm, with a mean of 5.23 cm (CV: 24.3 %), while the heartwood percentage ranged from 24.74 % to 31.84 %, averaging 27.66% (CV: 7.5 %), indicating consistent heartwood development across sites.

Overall analysis of variability revealed that sulphur (S), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) exhibited more than 50% coefficient of variation (CV) across ACZ-3, ACZ-4, ACZ-5, and ACZ-6. Additionally:

- Organic carbon (OC), nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca) showed CVs above 50% in ACZ-3 and ACZ-5.
- In ACZ-4, high variability (CV > 50%) was observed for OC, N, P, and K.
- Phosphorus (P), calcium (Ca), and electrical conductivity (EC) had CVs exceeding 50% in ACZ-6.
- Magnesium (Mg) showed more than 50% CV in ACZ-4, ACZ-5, and ACZ-6.

These findings highlight the spatial heterogeneity of both macro- and micronutrients in the study areas, which could significantly influence sandalwood growth and heartwood formation.

Assessment of mean and variability of tree parameters under ACZ-3, ACZ-4, ACZ-5 and ACZ-6

To understand the variability and performance of sandalwood growth attributes across locations, the observed values were categorized into four quadrants based on the overall mean and coefficient of variation (CV) for each trait—namely, tree height (mean: 8.8 m; CV: 14.5%), tree diameter (mean: 9.5 cm; CV: 15.7%), heartwood diameter (mean: 4.8 cm; CV: 21.3%), and heartwood percentage (mean: 26.0%; CV: 15.3%). Locations were grouped into the following four categories and are visualized in Figure 1: (i) Category I: Low mean and low CV, (ii) Category II: Low mean and high CV, (iii) Category III: High mean and low CV, and (iv) Category IV: High mean and high CV.

Category I: Low Mean and Low CV: Locations that exhibited both low averages and low variability included:

- Tree Height: 3 locations in ACZ-4 and 11 in ACZ-5
- Tree Diameter: 1 location in ACZ-3, 5 in ACZ-4, 10 in ACZ-5, and 2 in ACZ-6
- Heartwood Diameter: 6 locations in ACZ-4, 7 in ACZ-5, and 1 in ACZ-6
- Heartwood %: 3 locations in ACZ-3, 6 in ACZ-4, 9 in ACZ-5, and 1 in ACZ-6

Category II: Low Mean and High CV: Locations falling into this group had lower average values but higher variability:

- Tree Height: 8 locations in ACZ-3, 7 in ACZ-5, and 1 each in ACZ-4 and ACZ-6
- Tree Diameter: 1 location each in ACZ-3 and ACZ-6, 3 in ACZ-4, and 8 in ACZ-5
- Heartwood Diameter: 2 locations each in ACZ-3 and ACZ-6, 4 in ACZ-4, and 12 in ACZ-5
- Heartwood %: 2 locations in ACZ-3, 3 in ACZ-4, 6 in ACZ-5, and 1 in ACZ-6

Category III: High Mean and Low CV: These locations exhibited better mean performance with minimal variability:

- Tree Height: 5 locations each in ACZ-3 and ACZ-6, 4 in ACZ-4, and 3 in ACZ-5
- Tree Diameter: 7 locations in ACZ-3, 2 each in ACZ-4 and ACZ-6, and 3 in ACZ-5
- Heartwood Diameter: 8 locations in ACZ-3, 3 each in ACZ-4 and ACZ-6, and 4 in ACZ-5
- Heartwood %: 6 locations in ACZ-3, 2 each in ACZ-4 and ACZ-5, and 6 in ACZ-6

Category IV: High Mean and High CV: This group included locations with higher average values but also large variability:

- Tree Height: 2 locations each in ACZ-3 and ACZ-6, 3 in ACZ-4, and 5 in ACZ-5
- Tree Diameter: 6 locations in ACZ-3, 2 in ACZ-4, 5 in ACZ-5, and 3 in ACZ-6
- Heartwood Diameter: 5 locations in ACZ-3, 3 in ACZ-5, and 1 in ACZ-6
- Heartwood %: 4 locations in ACZ-3, 2 in ACZ-4, and 8 in ACZ-5

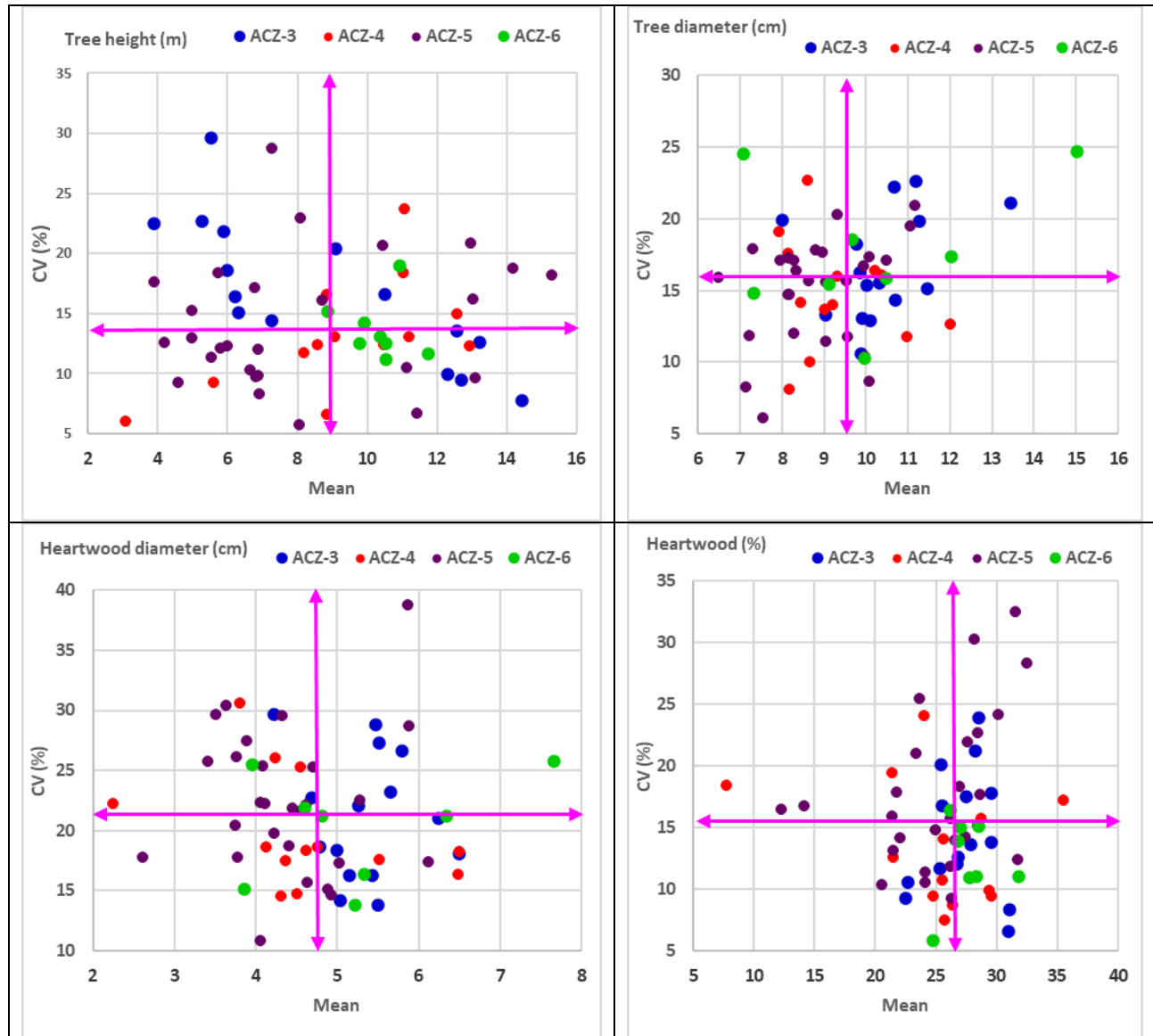


Fig 1. Mean and coefficient of variation of sandalwood tree parameters under ACZ-3, ACZ-4, ACZ-5 and ACZ-6

Descriptive statistics of soil and tree parameters under ACZ-7

The descriptive statistics of soil and sandalwood tree characteristics under ACZ-7, based on data from two locations, are presented in Table 4. The number of sandalwood trees per location ranged from 12 to 24, with a mean of 18 trees (CV: 47.1%), while the tree age varied from 7 to 9 years, averaging 8 years (CV: 17.7%).

Soil pH ranged between 7.01 and 8.78, with a mean of 7.9 (CV: 15.9%), indicating slightly alkaline soil. Electrical conductivity (EC) values ranged from 0.71 to 1.26 dS m⁻¹, with a mean of 0.99 dS m⁻¹ (CV: 39.5%), suggesting moderate salinity levels. Soil organic carbon (OC)

content ranged from 0.62% to 1.15%, with a mean of 0.89% (CV: 42.3%). Available nitrogen (N) ranged from 224.9 to 417.3 kg/ha, with a mean of 321.1 kg/ha (CV: 42.4%). Available phosphorus (P) ranged between 74.24 and 91.99 kg/ha, with a mean of 83.12 kg/ha (CV: 15.1%), and available potassium (K) varied from 252 to 582 kg/ha, averaging 417 kg/ha (CV: 56.0%). Calcium (Ca) levels ranged from 4046 to 6530 ppm, with a mean of 5288 ppm (CV: 33.2%), while magnesium (Mg) ranged from 778 to 1040 ppm, with a mean of 909 ppm (CV: 20.4%). Soil sulphur (S) was relatively stable, ranging from 198.43 to 225.3 ppm, with a mean of 211.87 ppm (CV: 9.0%). Micronutrient concentrations exhibited varying degrees of variability. Iron (Fe) ranged from 3.35 to 9.77 ppm (mean: 6.56 ppm, CV: 69.2%), manganese (Mn) from 1.8 to 1.97 ppm (mean: 1.89 ppm, CV: 6.4%), zinc (Zn) from 1.20 to 1.67 ppm (mean: 1.44 ppm, CV: 23.2%), and copper (Cu) from 0.95 to 1.65 ppm (mean: 1.3 ppm, CV: 38.1%).

In terms of tree growth characteristics, height ranged from 4.04 to 5.42 meters, with a mean of 4.73 m (CV: 20.6%). Diameter at breast height (DBH) varied from 6.81 to 10.3 cm, averaging 8.55 cm (CV: 28.9%). The heartwood diameter ranged from 3.28 to 5.11 cm, with a mean of 4.20 cm (CV: 30.8%), while heartwood content ranged narrowly between 25.12% and 26.23%, averaging 25.68% (CV: 3.1%), indicating consistency in heartwood formation within this zone.

Descriptive statistics of soil and tree parameters under ACZ-8

Descriptive statistics of soil and tree parameters recorded under Agro-Climatic Zone 8 (ACZ-8), based on data from two locations, are summarized in Table 4. Each location had 26 sandalwood trees, with tree ages ranging from 11 to 15 years and an overall mean age of 13 years (CV: 21.8%).

Soil pH values ranged from 7.00 to 7.55, with a mean of 7.28 (CV: 5.3%), indicating neutral to slightly alkaline soils. Electrical conductivity (EC) varied widely between 0.08 and 0.59 dS m⁻¹, with a mean of 0.34 dS m⁻¹ (CV: 106.5%), reflecting substantial variability in soil salinity. Organic carbon (OC) content ranged from 0.50% to 1.64%, with a mean of 1.07% (CV: 75.3%). Available nitrogen (N) ranged from 181.40 to 595.12 kg/ha, averaging 388.26 kg/ha (CV: 75.3%). Available phosphorus (P) levels varied from 26.2 to 81.6 kg/ha, with a mean of 53.9 kg/ha (CV: 72.7%), while potassium (K) ranged from 224 to 266 kg/ha, with a mean of 245 kg/ha (CV: 12.1%). Calcium (Ca) ranged from 2552 to 2765 ppm with a mean of 2658.5 ppm (CV: 5.7%), and magnesium (Mg) ranged from 360.0 to 379.5 ppm, averaging 369.75 ppm (CV: 3.7%), both showing relatively low variability. Micronutrient levels were more variable. Sulphur

(S) ranged from 17.33 to 116.00 ppm, with a mean of 66.67 ppm (CV: 104.7%). Iron (Fe) varied from 1.34 to 2.69 ppm, with a mean of 2.02 ppm (CV: 47.4%), while manganese (Mn) ranged from 1.74 to 2.71 ppm (mean: 2.23 ppm, CV: 30.8%). Zinc (Zn) content ranged from 1.35 to 2.23 ppm, averaging 1.79 ppm (CV: 34.8%), and copper (Cu) ranged from 0.36 to 1.77 ppm, with a mean of 1.07 ppm (CV: 93.6%).

Tree growth parameters exhibited low variation. Tree height ranged from 10.35 to 11.62 m, with a mean of 10.98 m (CV: 8.2%), and diameter at breast height (DBH) ranged from 9.42 to 10.01 cm, averaging 9.71 cm (CV: 4.3%). Heartwood diameter varied between 4.56 and 4.81 cm, with a mean of 4.68 cm (CV: 3.7%), while heartwood content was highly consistent, ranging from 23.68% to 23.93%, with a mean of 23.81% (CV: 0.7%).

Descriptive statistics of soil and tree parameters under ACZ-9

The descriptive statistics for soil and tree parameters under Agro-Climatic Zone 9 (ACZ-9), based on observations from two locations, are presented in Table 4. The number of sandalwood trees ranged from 21 to 25, with a mean of 23 trees per location (CV: 12.3%), and all trees were 15 years old.

Soil pH ranged from 6.58 to 7.01, with a mean value of 6.80 (CV: 4.5%), indicating near-neutral soil conditions. Electrical conductivity (EC) was low and stable, ranging from 0.01 to 0.02 dS m⁻¹, with a mean of 0.02 dS m⁻¹ (CV: 55.7%), reflecting minimal salinity variation.

Soil organic carbon (OC) content ranged between 0.29% and 0.48%, with a mean of 0.39% (CV: 34.9%). Available nitrogen (N) ranged from 105.23 to 174.18 kg/ha, averaging 139.71 kg/ha (CV: 34.9%). Available phosphorus (P) varied from 4.78 to 10.19 kg/ha, with a mean of 7.49 kg/ha (CV: 51.1%), while potassium (K) showed low variability, ranging from 308 to 336 kg/ha, with a mean of 322 kg/ha (CV: 6.1%).

Among soil cations, calcium (Ca) ranged from 2091.5 to 2529 ppm, with a mean of 2310.5 ppm (CV: 13.4%), while magnesium (Mg) ranged from 625.0 to 1260.5 ppm, averaging 942.75 ppm (CV: 47.7%). Sulphur (S) was present in the range of 10.0 to 18.1 ppm, with a mean of 14.05 ppm (CV: 40.8%). Iron (Fe) varied from 4.2 to 7.4 ppm (mean: 5.8 ppm, CV: 39.0%), while manganese (Mn) had a narrow range of 0.70 to 0.72 ppm, with a mean of 0.71 ppm (CV: 2.0%). Zinc (Zn) ranged widely from 0.17 to 3.72 ppm, with a mean of 1.95 ppm (CV: 129.1%), and copper (Cu) ranged from 0.15 to 0.40 ppm, averaging 0.28 ppm (CV: 64.3%).

Regarding tree parameters, height ranged from 9.88 to 11.38 m, with a mean of 10.63 m (CV:

10.0%), and diameter at breast height (DBH) varied from 8.53 to 12.17 cm, with a mean of 10.35 cm (CV: 24.9%). The heartwood diameter ranged from 4.51 to 6.31 cm, averaging 5.41 cm (CV: 23.5%), while heartwood content was highly consistent, ranging from 27.80% to 28.51%, with a mean of 28.16% (CV: 1.8%).

Descriptive statistics of soil and tree parameters under ACZ-10

The descriptive statistics for soil and tree parameters in Agro-Climatic Zone 10 (ACZ-10), based on data from two locations, are summarized in Table 4. The number of sandalwood trees ranged from 20 to 25, with a mean of 23 trees (CV: 15.7 %). The tree age ranged from 10 to 13 years, averaging 11.5 years (CV: 18.4 %). Soil pH remained constant at 7.0, while electrical conductivity (EC) was also consistent at 0.19 dS m⁻¹ at both locations. The soil had organic carbon (OC) content of 2.17 %, available nitrogen (N) of 787.44 kg/ha, phosphorus (P) of 16.27 kg/ha, and potassium (K) of 266 kg/ha. Macronutrient levels were uniformly high. Micronutrient concentrations included calcium (Ca) at 2658 ppm, magnesium (Mg) at 324 ppm, sulphur (S) at 64.11 ppm, iron (Fe) at 9.45 ppm, manganese (Mn) at 2.1 ppm, zinc (Zn) at 0.93 ppm, and copper (Cu) at 0.13 ppm. In terms of tree metrics, height ranged from 7.75 to 8.36 m, with a mean of 8.06 m (CV: 5.4 %), and diameter at breast height (DBH) ranged from 6.60 to 7.33 cm, averaging 6.96 cm (CV: 7.4 %). Heartwood diameter varied from 3.28 to 3.87 cm, with a mean of 3.58 cm (CV: 11.7 %), while heartwood content ranged from 25.04 % to 28.58 %, averaging 26.81 % (CV: 9.3 %).

Table 4. Descriptive statistics of different soil and tree parameters in ACZ-2, 7, 8, 9, 10 (10 locations)

Parameter	ACZ-2 (2)		ACZ-7 (2)		ACZ-8 (2)		ACZ-9 (2)		ACZ-10 (2)	
	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
pH	7.61	11.1	7.90	15.9	7.28	5.3	6.80	4.5	7.0	#
EC	0.44	17.9	0.99	39.5	0.34	106.5	0.02	55.7	0.19	#
OC	1.04	15.0	0.89	42.3	1.07	75.3	0.39	34.9	2.17	#
N	377.35	15.0	321.10	42.4	388.26	75.3	139.71	34.9	787.44	#
P	35.23	15.1	83.12	15.1	53.90	72.7	7.49	51.1	16.27	#
K	252.00	55.0	417.00	56.0	245.00	12.1	322	6.1	266	#
Ca	4589.75	27.9	5288.00	33.2	2658.5	5.7	2310.25	13.4	2658	#
Mg	658.50	16.4	909.00	20.4	369.75	3.7	942.75	47.7	324	#
S	191.68	3.6	211.87	9.0	66.67	104.7	14.05	40.8	64.11	#
Fe	6.98	57.3	6.56	69.2	2.02	47.4	5.80	39.0	9.45	#
Mn	2.18	53.6	1.89	6.4	2.23	30.8	0.71	2.0	2.1	#
Zn	1.70	8.3	1.44	23.2	1.79	34.8	1.95	129.1	0.93	#
Cu	0.70	20.2	1.30	38.1	1.07	93.6	0.28	64.3	0.13	#

Trees	25		18	47.1	26		23	12.3	23	15.7
TA	7		8	17.7	13	21.8	15		11.5	18.4
TH	6.32	9.0	4.73	20.6	10.98	8.2	10.63	10.0	8.06	5.4
TD	8.62	3.6	8.55	28.9	9.71	4.3	10.35	24.9	6.96	7.4
HWD	3.89	3.8	4.20	30.8	4.68	3.7	5.41	23.5	3.58	11.7
HW	20.73	1.6	25.68	3.1	23.81	0.7	28.16	1.8	26.81	9.3

#: Both locations have same values

Descriptive statistics of soil and tree parameters when pooled over all ACZs

The pooled descriptive statistics of soil and tree parameters collected across 73 locations spanning 9 Agro-Climatic Zones (ACZs) are presented in Table 5. The number of sandalwood trees per location varied from 10 to 30, with a mean of 22.15 trees (CV: 23.1%). Tree age ranged from 5 to 17 years, averaging 10.2 years (CV: 27.5%).

Soil pH ranged from 5.52 to 8.78, with a mean of 6.99 and a relatively low variability (CV: 9.6%), indicating moderate to slightly alkaline conditions across most sites. In contrast, electrical conductivity (EC) showed high heterogeneity, ranging from 0.01 to 1.26 dS m⁻¹ with a mean of 0.2 dS m⁻¹ (CV: 94.3%), suggesting significant spatial differences in soil salinity. Organic carbon (OC) content varied from 0.02 to 2.17%, with a mean of 0.58% (CV: 83.8%). Similarly, available nitrogen (N) ranged widely from 7.25 to 787.44 kg/ha, with a mean of 203.48 kg/ha (CV: 86.1%). Soil phosphorus (P) and potassium (K) showed ranges of 0.42–145 kg/ha (mean: 31.47 kg/ha, CV: 85.6%) and 140–1400 kg/ha (mean: 459.3 kg/ha, CV: 70.0%), respectively. Among micronutrients, calcium (Ca) exhibited a vast range from 333 to 24,115 ppm, averaging 3422.08 ppm (CV: 109.3%), while magnesium (Mg) ranged from 52.5 to 1471 ppm (mean: 466.67 ppm, CV: 65.0%). Sulphur (S) ranged from 0.62 to 225.3 ppm, with a mean of 56.59 ppm (CV: 129.8%), indicating extreme variability across sites. Likewise, high CVs were recorded for iron (Fe) (range: 0.12–46.8 ppm, mean: 10.3 ppm, CV: 89.8%), manganese (Mn) (range: 0.12–14 ppm, mean: 2.11 ppm, CV: 100.0%), zinc (Zn) (range: 0.03–9.87 ppm, mean: 1.04 ppm, CV: 138.9%), and copper (Cu) (range: 0.07–8.12 ppm, mean: 1.5 ppm, CV: 94.1%), further emphasizing the spatial diversity in soil nutrient status.

Regarding tree growth parameters, tree height ranged from 3.08 to 15.29 m, with a mean of 8.73 m (CV: 34.5%), and diameter at breast height (DBH) varied between 6.51 to 15.02 cm (mean: 9.38 cm, CV: 16.8%). Heartwood diameter ranged from 2.25 to 7.67 cm, with a mean of 4.72 cm (CV: 20.5%), while heartwood content varied from 7.77 to 35.49%, averaging 25.86% (CV: 16.8%).

The findings align with earlier observations by Shoba Rai (1990), who reported comparable ranges in heartwood formation and tree growth in *Santalum album* across diverse conditions. From the current dataset, it was evident that all soil parameters except pH exhibited CVs exceeding 50%, highlighting substantial spatial variability. Additionally, when data were analyzed specifically across 10 locations under ACZ-2, ACZ-7, ACZ-8, ACZ-9, and ACZ-10, the parameters EC, OC, N, P, Mg, S, Fe, Zn, and Cu also recorded CVs greater than 50%, indicating a consistent pattern of variability in key soil fertility attributes across zones.

Table 5. Descriptive statistics of soil and tree parameters when pooled over ACZs

Parameter	Pooled over all ACZs (73)	
	Mean	CV (%)
pH	6.99	9.6
EC	0.20	94.3
OC	0.58	83.8
N	203.48	86.1
P	31.47	85.6
K	459.30	70.0
Ca	3422.08	109.3
Mg	466.67	65.0
S	56.59	129.8
Fe	10.30	89.8
Mn	2.11	100.0
Zn	1.04	138.9
Cu	1.50	94.1
Trees	22.15	23.1
TA	10.23	27.5
TH	8.73	34.5
TD	9.38	16.8
HWD	4.72	20.5
HW	25.86	16.8

Assessment of mean and variability of tree parameters under different ACZs

Across the two locations in ACZ-2, one exhibited a '*low mean and low variation*' in tree height, while the other showed a '*low mean and high variation*'. Both locations in ACZ-7 were characterized by '*low mean and high variation*', whereas both locations in ACZ-8 had '*high mean and low variation*'. In ACZ-9, one location demonstrated '*high mean and low variation*', and the other had '*high mean and high variation*'. For ACZ-10, one site showed '*low mean and low variation*', and the other '*high mean and low variation*' in tree height.

When evaluating tree diameter across 10 locations under ACZ-2, ACZ-7, ACZ-8, ACZ-9, and ACZ-10, both locations in ACZ-2 and ACZ-10 fell under the '*low mean and low variation*'

category. In contrast, both locations in ACZ-8 exhibited '*high mean and low variation*'. Within ACZ-7, one location showed '*low mean and high variation*', and the other '*high mean and high variation*'. In ACZ-9, the locations were categorized as '*low mean and low variation*' and '*high mean and high variation*', respectively.

For heartwood diameter, the sites in ACZ-2 and ACZ-10 were again grouped under '*low mean and low variation*', while both locations in ACZ-8 showed '*high mean and low variation*'. In ACZ-7, one site fell under '*low mean and high variation*' and the other under '*high mean and high variation*'. In ACZ-9, one location had '*high mean and low variation*', while the other showed '*high mean and high variation*'.

Regarding heartwood content (%), both locations in ACZ-2 were classified under '*low mean and high variation*', while both in ACZ-10 exhibited '*high mean and low variation*'. In ACZ-7, one location had '*low mean and high variation*' and the other '*high mean and high variation*'. In ACZ-8 and ACZ-9, each had one location with '*high mean and low variation*' and another with '*high mean and high variation*'.

An assessment across ACZ-3, ACZ-4, ACZ-5, and ACZ-6 revealed the following trends:

- Tree height: The majority of locations exhibited '*low mean and low CV*', followed by '*high mean and low CV*', '*low mean and high CV*', and '*high mean and high CV*'.
- Tree diameter: Most locations had '*low mean and low CV*', followed by '*low mean and high CV*', '*high mean and high CV*', and '*high mean and low CV*'.
- Heartwood diameter: The dominant category was '*low mean and low CV*', followed by '*high mean and low CV*', '*low mean and high CV*', and '*high mean and high CV*'.
- Heartwood (%): Most locations showed '*high mean and low CV*', followed by '*high mean and high CV*', and '*low mean and low CV*'.

When the data were pooled across all 73 locations, most locations showed '*low mean and low variation*' for tree height and tree diameter, while heartwood diameter and heartwood (%) were predominantly categorized as '*high mean and low variation*', followed by '*low mean and high variation*'.

Testing the differences between tree parameters under ACZ-3, ACZ-4, ACZ-5 and ACZ-6

The mean differences in sandalwood tree height (m), tree diameter (cm), heartwood diameter (cm), and heartwood percentage (%) across each pair of agro-climatic zones (ACZ-3, ACZ-4, ACZ-5, and ACZ-6) were evaluated using the Student's t-test. The results, including the

mean difference, standard error of mean (SEM), t-calculated (t-cal), and t-critical (t-cri) values, along with the significance levels, are presented in Table 6 (tree height), Table 7 (tree diameter), Table 8 (heartwood diameter), and Table 9 (heartwood percentage).

Based on the t-test results, no significant differences were observed in the mean tree height between any of the ACZ pairs, viz., (i) ACZ-3 (8.7 m) and ACZ-4 (9.4 m); (ii) ACZ-3 (8.7 m) and ACZ-5 (8.2 m); (iii) ACZ-3 (8.7 m) and ACZ-6 (10.3 m); (iv) ACZ-4 (9.4 m) and ACZ-5 (8.2 m); (v) ACZ-4 (9.4 m) and ACZ-6 (10.3 m); and (vi) ACZ-5 (8.2 m) and ACZ-6 (10.3 m). These results indicate that, over time, the mean tree height of sandalwood trees did not differ significantly across the studied agro-climatic zones of Karnataka, suggesting a comparable growth performance under varied climatic conditions.

Table 6. Testing differences of tree height attained under ACZ-3, ACZ-4, ACZ-5, ACZ-6

ACZ	N	Mean	SD	Mean difference	SEM	t-cal	t-cri (5%)	t-cri (1%)	Significance
3	15	8.7	3.5	-0.612	1.21	-0.507	2.056	2.779	NS
4	13	9.4	2.7						
3	15	8.7	3.5	0.579	1.09	0.530	2.021	2.704	NS
5	27	8.2	3.3						
3	15	8.7	3.5	-1.596	1.28	-1.248	2.080	2.831	NS
6	8	10.3	0.9						
4	13	9.4	2.7	1.191	1.06	1.123	2.026	2.715	NS
5	27	8.2	3.3						
4	13	9.4	2.7	-0.984	1.01	-0.979	2.093	2.861	NS
6	8	10.3	0.9						
5	27	8.2	3.3	-2.175	1.19	-1.823	2.036	2.738	NS
6	8	10.3	0.9						

NS: Not significant

SEM: Standard error of mean

Among the six pairwise comparisons, significant differences in mean tree diameter of sandalwood were observed in the following cases based on the Student's t-test (as shown in Table 7): (i) ACZ-3 (10.4 cm) vs. ACZ-4 (9.3 cm) – The mean diameter under ACZ-3 was significantly higher than that under ACZ-4 at the 5% level of significance. (ii) ACZ-3 (10.4 cm) vs. ACZ-5 (8.9 cm) – The mean diameter under ACZ-3 was significantly higher than that under ACZ-5 at the 1% level of significance.

In contrast, no statistically significant differences in tree diameter were observed between the

following pairs: (i) ACZ-3 (10.4 cm) and ACZ-6 (10.1 cm); (ii) ACZ-4 (9.3 cm) and ACZ-5 (8.9 cm); (iii) ACZ-4 (9.3 cm) and ACZ-6 (10.1 cm); and (iv) ACZ-5 (8.9 cm) and ACZ-6 (10.1 cm) zones. These results indicate that sandalwood trees under ACZ-3 exhibited a statistically superior mean diameter compared to those under ACZ-4 and ACZ-5, while the differences among the other zones were not statistically significant.

Table 7. Testing differences of tree diameter attained under ACZ-3, ACZ-4, ACZ-5, ACZ-6

ACZ	N	Mean	SD	Mean difference	SEM	t-cal	t-crit (5%)	t-crit (1%)	Significance
3	15	10.4	1.2	1.052	0.46	2.268	2.056	2.779	*
4	13	9.3	1.2						
3	15	10.4	1.2	1.523	0.39	3.898	2.021	2.704	**
5	27	8.9	1.2						
3	15	10.4	1.2	0.288	0.78	0.369	2.080	2.831	NS
6	8	10.1	2.6						
4	13	9.3	1.2	0.471	0.41	1.147	2.026	2.715	NS
5	27	8.9	1.2						
4	13	9.3	1.2	-0.764	0.83	-0.925	2.093	2.861	NS
6	8	10.1	2.6						
5	27	8.9	1.2	-1.235	0.64	-1.921	2.036	2.738	NS
6	8	10.1	2.6						

NS: Not significant

SEM: Standard error of mean

* and ** indicate significance at 5% and 1% level respectively

Among the six pairwise comparisons, significant differences in mean heartwood diameter of sandalwood trees were observed in the following cases based on the Student's t-test (refer to Table 8): (i) ACZ-3 (5.35 cm) vs. ACZ-5 (4.40 cm) – The mean heartwood diameter under ACZ-3 was significantly higher than that under ACZ-5 at the 5% level of significance. (ii) ACZ-4 (4.62 cm) vs. ACZ-5 (4.40 cm) – The mean diameter under ACZ-4 was also significantly higher than ACZ-5 at the 5% level of significance. (iii) ACZ-4 (4.62 cm) vs. ACZ-6 (5.23 cm) – The mean diameter under ACZ-6 was significantly higher than that of ACZ-4 at the 5% level of significance. (iv) ACZ-5 (4.40 cm) vs. ACZ-6 (5.23 cm) – The heartwood diameter under ACZ-6 was significantly higher than ACZ-5 at the 1% level of significance.

On the other hand, the difference in heartwood diameter between ACZ-3 (5.35 cm) and ACZ-6 (5.23 cm) was not statistically significant, indicating comparable heartwood development in

these zones. These results suggest that ACZ-5 consistently showed the lowest mean heartwood diameter, significantly lagging behind ACZ-3, ACZ-4, and ACZ-6.

Table 8. Testing differences of heartwood diameter attained under ACZ-3, ACZ-4, ACZ-5, ACZ-6

ACZ	N	Mean	SD	Mean difference	SEM	t-cal	t-crit (5%)	t-crit (1%)	Significance
3	15	5.35	0.58	0.728	0.33	2.218	2.056	2.779	NS
4	13	4.62	1.11						
3	15	5.35	0.58	0.952	0.24	4.045	2.021	2.704	*
5	27	4.40	0.80						
3	15	5.35	0.58	0.124	0.57	0.219	2.080	2.831	NS
6	8	5.23	2.09						
4	13	4.62	1.11	0.224	0.31	0.729	2.026	2.715	*
5	27	4.40	0.80						
4	13	4.62	1.11	-0.603	0.69	-0.869	2.093	2.861	*
6	8	5.23	2.09						
5	27	4.40	0.80	-0.827	0.48	-1.718	2.036	2.738	**
6	8	5.23	2.09						

NS: Not significant

SEM: Standard error of mean

* and ** indicate significance at 5% and 1% level respectively

Among the six pairwise comparisons, significant differences in mean heartwood percentage of sandalwood trees were observed in the following cases, as per the Student's t-test (refer to Table 9): (i) ACZ-3 (27.22%) vs. ACZ-6 (27.66%) – The mean heartwood percentage under ACZ-6 was significantly higher than that of ACZ-3 at the 5% level of significance. (ii) ACZ-5 (25.24%) vs. ACZ-6 (27.66%) – The mean heartwood under ACZ-6 was significantly higher than that under ACZ-5 at the 1% level of significance.

However, the differences in mean heartwood percentage were not statistically significant for the following pairs: (i) ACZ-3 (27.22%) vs. ACZ-4 (25.09%), (ii) ACZ-3 (27.22%) vs. ACZ-5 (25.24%), (iii) ACZ-4 (25.09%) vs. ACZ-5 (25.24%) and (iv) ACZ-4 (25.09%) vs. ACZ-6 (27.66%). These results indicate that ACZ-6 consistently demonstrated higher heartwood content, significantly outperforming ACZ-3 and ACZ-5, while the differences involving ACZ-4 were not significant.

Table 9. Testing differences of heartwood attained under ACZ-3, ACZ-4, ACZ-5, ACZ-6

ACZ	N	Mean	SD	Mean difference	SE	t-cal	t-crit (5%)	t-crit (1%)	Significance
3	15	27.22	2.63	2.129	1.80	1.182	2.056	2.779	NS
4	13	25.09	6.39						
3	15	27.22	2.63	1.977	1.34	1.477	2.021	2.704	NS
5	27	25.24	4.78						
3	15	27.22	2.63	-0.441	0.99	-0.444	2.080	2.831	*
6	8	27.66	1.27						
4	13	25.09	6.39	-0.152	1.80	-0.084	2.026	2.715	NS
5	27	25.24	4.78						
4	13	25.09	6.39	-2.570	2.31	-1.113	2.093	2.861	NS
6	8	27.66	1.27						
5	27	25.24	4.78	-2.418	1.72	-1.403	2.036	2.738	**
6	8	27.66	1.27						

NS: Not significant SEM: Standard error of mean
 * and ** indicate significance at 5% and 1% level respectively

Superiority of ACZs based on the performance of sandalwood tree and soil parameters

To evaluate the suitability of different Agro-Climatic Zones (ACZs) for sandalwood cultivation, ranks were assigned to the mean values of key parameters observed under each ACZ across four categories:

1. Tree growth and wood parameters: heartwood content, heartwood diameter, tree height, and tree diameter
2. Soil reaction parameters: soil pH and electrical conductivity
3. Soil macro-nutrient parameters: organic carbon, nitrogen (N), phosphorus (P), and potassium (K)
4. Soil micro-nutrient parameters: calcium (Ca), magnesium (Mg), sulphur (S), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu)

For each category, ranks were assigned based on the magnitude of the respective parameters, with the lowest rank sum indicating superiority in terms of suitability for sandalwood cultivation. An overall rank sum was then computed by aggregating the rank sums across all categories for each ACZ.

The results are presented as follows: Rank sums of tree parameters (RS1) in Table 10, Rank sums of soil pH and electrical conductivity (RS2) in Table 11, Rank sums of soil macro-nutrients (RS3) in Table 12 and Rank sums of soil micro-nutrients (RS4) in Table 13.

The ACZ with the lowest overall rank sum was identified as the most suitable zone for sandalwood cultivation, with other ACZs ranked accordingly based on the cumulative rank sums of soil and tree parameters.

The rank sums of tree parameters (RS1) revealed that ACZ-9 was the most favourable zone for sandalwood cultivation, with the lowest rank sum of 6. This zone secured the 1st rank for both heartwood percentage and heartwood diameter, and the 2nd rank for tree height and tree diameter, indicating superior tree growth performance compared to other ACZs. ACZ-3 and ACZ-6 followed closely, each with a rank sum of 11, making them the second-best zones based on tree parameter rankings (Table 10).

Table 10. Superiority of ACZs based on ranking of sandalwood tree parameters

ACZ	HW (%)	HDW (cm)	TH (m)	TD (cm)	HW	HDW	TH	TD	RS1
2	20.73	3.89	6.3	8.6	9	8	8	8	33
3	27.22	5.35	8.7	10.4	3	2	5	1	11
4	25.09	4.62	9.4	9.3	7	5	4	5	21
5	25.24	4.40	8.2	8.9	6	6	6	6	24
6	27.66	5.23	10.3	10.1	2	3	3	3	11
7	25.68	4.20	4.7	8.6	5	7	9	7	28
8	23.81	4.68	11.0	9.7	8	4	1	4	17
9	28.16	5.41	10.6	10.3	1	1	2	2	6
10	26.81	3.58	8.1	7.0	4	9	7	9	29

Regarding soil pH and electrical conductivity (RS2), ACZ-6 and ACZ-9 again emerged as the most suitable zones, each attaining a rank sum of 9. ACZ-6 secured the 1st rank for soil pH, while ACZ-7 achieved the 1st rank for electrical conductivity. The next best-performing zones—ACZ-2, ACZ-3, ACZ-5, ACZ-7, and ACZ-8—shared second position, based on the combined rankings of soil pH and EC (Table 11).

Table 11. Superiority of ACZs based on ranking of soil pH and electrical conductivity parameters

ACZ	pH (1:2.5)	EC (dS/m)	pH (1:2.5)	EC (dS/m)	RS2
2	7.61	0.44	8	2	10
3	7.19	0.30	6	4	10
4	7.04	0.15	5	6	11
5	6.87	0.14	3	7	10

6	6.53	0.06	1	8	9
7	7.90	0.99	9	1	10
8	7.28	0.34	7	3	10
9	6.80	0.02	2	9	11
10	7.00	0.19	4	5	9

The rank sums of soil macro-nutrients (RS3) revealed that ACZ-7 was the most favourable zone, securing the lowest rank sum of 13, indicating superior soil fertility in terms of macronutrient availability. In contrast, ACZ-9 recorded the highest rank sum of 31, reflecting comparatively lower macronutrient status. Among the individual nutrients, ACZ-10 ranked 1st for both organic carbon and nitrogen, ACZ-7 ranked 1st for phosphorus, and ACZ-4 attained 1st rank for potassium. ACZ-8 emerged as the second-best zone with a rank sum of 15, based on macronutrient performance (Table 12).

Table 12. Superiority of ACZs based on ranking of soil organic carbon, N, P and K parameters

ACZ	OC (%)	N (kg/ha)	P (kg/ha)	K (kg/ha)	OC (%)	N (kg/ha)	P (kg/ha)	K (kg/ha)	RS3
2	1.04	377.35	35.23	252.00	3	3	4	8	18
3	0.51	163.99	33.90	463.07	7	7	5	2	21
4	0.36	127.35	37.98	661.08	9	9	3	1	22
5	0.53	185.13	27.92	455.96	6	6	6	3	21
6	0.59	214.08	18.68	334.25	5	5	7	5	22
7	0.89	321.10	83.12	417.00	4	4	1	4	13
8	1.07	388.26	53.90	245.00	2	2	2	9	15
9	0.39	139.71	7.49	322.00	8	8	9	6	31
10	2.17	787.44	16.27	266.00	1	1	8	7	17

For soil micro-nutrients (RS4), ACZ-2 stood out as the best-performing zone with the lowest rank sum of 25, while ACZ-6 ranked the lowest with the highest rank sum of 53. Zone-wise top performers for individual micronutrients were as follows: ACZ-3 for calcium, ACZ-9 for magnesium and zinc, ACZ-7 for sulphur, ACZ-4 for iron and manganese, and ACZ-5 for copper. ACZ-7, with a rank sum of 26, was identified as the second-best zone for micro-nutrient availability (Table 13).

Table 13. Superiority of ACZs based on ranking of soil micro-nutrient parameters

ACZ	Ca	Mg	S	Fe	Mn	Zn	Cu	Ca	Mg	S	Fe	Mn	Zn	Cu	RS4
2	4589.75	658.50	191.68	6.98	2.18	1.70	0.70	3	3	2	5	3	3	6	25
3	8078.47	559.05	103.11	9.97	1.34	1.49	1.53	1	5	3	3	8	4	3	27
4	1784.42	611.92	21.28	14.18	3.46	0.88	1.94	8	4	8	1	1	7	2	31
5	2185.24	309.06	31.50	11.74	2.12	0.77	1.96	7	9	7	2	4	8	1	38
6	1428.31	371.68	45.11	4.94	1.65	0.72	0.23	9	6	6	8	7	9	8	53
7	5288.00	909.00	211.87	6.56	1.89	1.44	1.30	2	2	1	6	6	5	4	26

8	2658.50	369.75	66.67	2.02	2.23	1.79	1.07	4	7	4	9	2	2	5	33
9	2310.25	942.75	14.05	5.80	0.71	1.95	0.28	6	1	9	7	9	1	7	40
10	2658.00	324.00	64.11	9.45	2.10	0.93	0.13	5	8	5	4	5	6	9	42

The rank analysis revealed that ACZ-9 was the most favorable zone for sandalwood tree parameters, while ACZ-6 and ACZ-9 were superior with respect to soil pH and electrical conductivity. In terms of soil macro-nutrients, ACZ-7 ranked highest, and ACZ-2 emerged as the best zone for soil micro-nutrients. However, when considering the overall rank sum derived by combining soil and tree parameters across all categories, ACZ-3 stood out as the most suitable zone for sandalwood cultivation, with the lowest total rank sum of 69. This was followed by ACZ-8 with a rank sum of 75, and ACZ-7 with 77, indicating their strong potential for supporting healthy and productive sandalwood trees. In contrast, ACZ-10 was ranked the lowest, with the highest rank sum of 97, suggesting limited suitability. The relative superiority of the agro-climatic zones (ACZs) for efficient sandalwood cultivation, based on composite rankings of soil and tree parameters, is illustrated in Figure 1.

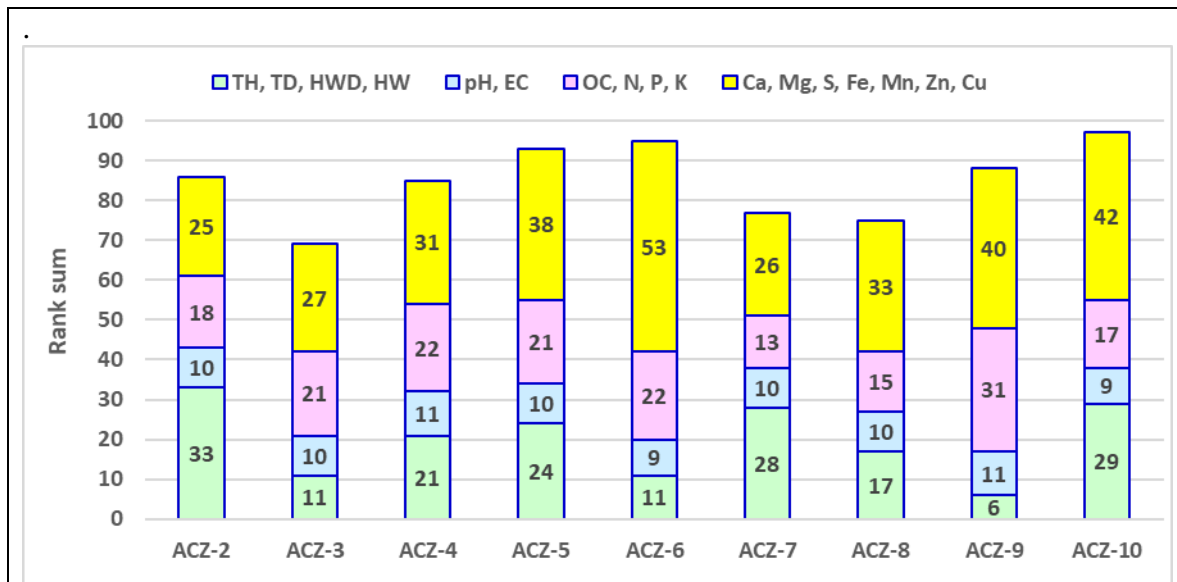


Fig 1. Superiority of Agro-climatic zones based on rank sum of soil and sandalwood tree parameters

Conclusions

This study presents a detailed evaluation of sandalwood (*Santalum album* L.) growth and soil fertility parameters across nine Agro-Climatic Zones (ACZs) in Karnataka, based on observations from 73 taluks. The analysis captures the variability in soil and climatic conditions and their impact on tree performance, culminating in a comparative ranking of zones for sandalwood cultivation.

Rainfall exhibited a wide range from 266.5 mm to 1376.4 mm (mean: 471 mm; CV: 56.9%), highlighting substantial variation. In contrast, temperature showed limited variability, ranging from 23.7°C to 28.0°C (mean: 25.2°C; CV: 4.4%). These environmental factors influence soil nutrient dynamics—while higher rainfall may enhance nutrient availability, it can also increase nutrient leaching.

Tree age varied across zones, ranging from 9.5 years in ACZ-4 to 11.5 years in ACZ-6, with CVs between 21.1% and 36.0%, indicating moderate to high variation in stand maturity. The number of study locations also differed, with ACZ-5 having the highest (27 locations) and ACZ-6 the lowest (8 locations), reflecting differences in the extent of sandalwood cultivation.

Soil pH ranged from 6.53 (ACZ-6) to 7.31 (pooled ACZ-2, 7, 8, 9, 10), indicating soils that are slightly acidic to neutral—conditions generally favorable for sandalwood. Electrical Conductivity (EC) ranged from 0.06 to 0.39 dS/m, with high variability (CV: 50.2%–99.4%), suggesting inconsistent salinity levels. Organic Carbon (OC) ranged from 0.36% to 1.11%, with high CVs (61.9%–94.6%), reflecting spatial differences in organic matter content. Nitrogen (N) ranged from 127.35 to 402.77 kg/ha (CV: 61.9%–90.4%), while Phosphorus (P) varied from 18.68 to 39.2 kg/ha (CV: 67.0%–81.2%). Potassium (K) levels ranged from 300.4 to 661.08 kg/ha (CV: 37.8%–68.2%).

Among micronutrients: Calcium (Ca): 1428.38–8078.47 ppm (CV: 60.3%–73.2%), Magnesium (Mg): 309.06–640.8 ppm (CV: 50.0%–53.8%), Sulphur (S): 21.29–109.67 ppm with extreme variation (CV: 151.0% in ACZ-4), Iron (Fe): 4.94–14.18 ppm (CV: 62.1%–106.1%), Manganese (Mn): 1.34–3.46 ppm (CV: 86.0%–107.1%), Zinc (Zn): 0.72–1.56 ppm (CV: 60.8%–89.0%), Copper (Cu): 0.23–1.96 ppm (CV: 78.6%–84.8%). High coefficients of variation for most nutrients suggest significant spatial heterogeneity, likely affecting sandalwood performance across zones.

Tree height ranged from 8.14 m to 10.34 m (CV: 8.3%–32.2%). No statistically significant differences were detected among ACZs, indicating that height may be less influenced by agro-climatic variation. Tree diameter ranged from 8.84 cm to 10.37 cm (CV: 11.8%–19.5%), with significant differences observed between: (i) ACZ-3 (10.4 cm) and ACZ-4 (9.3 cm) – significant at 5%, (ii) ACZ-3 (10.4 cm) and ACZ-5 (8.9 cm) – significant at 1%. Heartwood diameter varied between 4.35 cm and 5.35 cm (CV: 10.9%–21.2%), with significant differences between several zone pairs, notably: ACZ-3 vs. ACZ-5, ACZ-4 vs. ACZ-6, and ACZ-5 vs. ACZ-6. Heartwood

content (%) ranged from 25.04% to 27.66% (CV: 7.5%–11.5%). Noteworthy differences included: (i) ACZ-6 (27.66%) significantly higher than ACZ-3 (27.22%) – 5% significance, (ii) ACZ-6 (27.66%) significantly higher than ACZ-5 (25.24%) – 1% significance. These results highlight ACZ-3 and ACZ-6 as favorable zones for enhanced heartwood development and tree diameter, both of which are key economic traits for sandalwood cultivation.

The rank-based analysis of tree growth and soil parameters across Agro-Climatic Zones (ACZs) offers critical insights into the optimal regions for sandalwood (*Santalum album* L.) cultivation in Karnataka.

1. Tree Growth Parameters (RS1): ACZ-9 emerged as the most favorable zone for sandalwood growth, with the lowest rank sum (6). It secured the 1st rank for heartwood content and heartwood diameter, and the 2nd rank for tree height and tree diameter, reflecting superior performance across all tree growth metrics.
2. Soil Reaction and Salinity (RS2): ACZ-6 and ACZ-9 ranked highest for soil pH and electrical conductivity (rank sum: 9), indicating that these zones possess optimal pH and salinity levels, essential for root activity and nutrient uptake.
3. Soil Macronutrients (RS3): ACZ-7 was ranked best for macronutrient availability (rank sum: 13), indicating higher levels of key nutrients such as Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), and Sulphur (S), which are vital for overall tree vigor and productivity. ACZ-8 followed closely with a rank sum of 15.
4. Soil Micronutrients (RS4): ACZ-2 topped the rankings for micronutrients (rank sum: 25), suggesting greater availability of Iron (Fe), Manganese (Mn), Zinc (Zn), and Copper (Cu)—critical elements for enzymatic and physiological functions in trees.

Overall Suitability for Sandalwood Cultivation, Considering the combined performance across all categories: (i) ACZ-3 achieved the lowest overall rank sum (69), making it the most suitable zone for sandalwood cultivation. (ii) ACZ-8 followed as the second-best zone (rank sum: 75), highlighting a favourable combination of soil fertility and tree growth potential. (iii) ACZ-7 and ACZ-6 ranked third and fourth, respectively.

Recommendations and Interpretations

- ACZ-3 and ACZ-8 are recommended as priority zones for sandalwood cultivation due to their balanced soil fertility and superior tree growth attributes. ACZ-3, with high calcium availability, supports greater tree diameter and heartwood formation, while ACZ-8 presents a

well-balanced nutrient profile.

- ACZ-6 is particularly favorable for heartwood content and heartwood diameter, likely attributed to its neutral soil pH (6.53) and very low EC (0.06 dS/m), conditions that reduce physiological stress and promote heartwood accumulation.
- To optimize heartwood production, which directly correlates with sandalwood's economic value, cultivation efforts should be concentrated in ACZ-3 and ACZ-6.
- Soil amendments are suggested for zones with nutritional deficiencies—e.g., ACZ-6 (low in phosphorus) and ACZ-4 (low in sulphur)—to improve tree growth outcomes.

Further research is recommended to correlate specific soil nutrients (e.g., Ca, K, Mg) with heartwood formation, enabling precision cultivation strategies. These findings are not only applicable across Karnataka's ACZs but can also inform site selection and soil management for sandalwood plantations under similar agro-climatic conditions elsewhere.

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B.N.D. conceptualized, planned, and executed the fieldwork, and led the drafting of the manuscript.

G.R.M.S. assisted in data analysis, compilation, and contributed to the manuscript drafting by reviewing the manuscript and provided valuable suggestions for its improvement.

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