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Assessment of Performance of Sandalwood Grown under Different Agro-Climatic Zones of Karnataka Based on Relationship and Principal Component Analysis

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Abstract

Santalum album L. (sandalwood) is a highly valued tree species cultivated for its heartwood and essential oil. The present study assessed the growth performance and adaptability of sandalwood across different agro-climatic zones (ACZs) of Karnataka, India, by examining relationships among growth, yield, soil, and weather parameters using correlation analysis and Principal Component Analysis (PCA). A total of 73 field plots were established on farmers' lands, with plot sizes ranging from 110 m^2 to 533 m^2, ensuring the inclusion of at least 25 - 30 sandalwood trees per plot. Growth attributes (tree height, diameter at breast height, and heartwood diameter), heartwood yield, soil fertility characteristics, and weather variables were recorded and analyzed. Annual rainfall varied from 266.5 mm to 1376.4 mm (mean: 471 mm; CV: 56.9%), while mean temperature ranged from 23.7˚C to 28.0˚C (mean: 25.2˚C; CV: 4.4%). Rainfall exhibited a positive correlation with heartwood percentage in ACZ-5 ($r = 0.396$) and pooled ACZs (2, 7, 8, 9, and 10) ($r = 0.667$). In contrast, temperature showed negative associations with heartwood percentage in ACZ-5 ($r = -0.483$) and heartwood diameter in ACZ-6 ($r = -0.730$). Organic carbon was positively correlated with soil nitrogen across ACZ-3 to ACZ-6 and pooled zones, while tree diameter demonstrated a strong positive relationship with heartwood content in these regions. Significant associations among calcium, magnesium, and sulphur were observed in ACZ-3, ACZ-4, and ACZ-5. Heartwood content was influenced by tree age in ACZ-3, ACZ-5, and pooled zones, whereas tree height and heartwood diameter were important determinants in ACZ-4. PCA identified major soil fertility parameters driving growth variability, with strong loadings for pH, electrical conductivity (EC), organic carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, copper, and zinc. Five principal components explained 77.07% of the total variance in ACZ-5, four components explained 79.09% - 85.87% in ACZ-4, ACZ-6, and pooled ACZs, and three components accounted for 74.01% in ACZ-3. Soil properties, particularly pH, EC, calcium, magnesium, and sulphur, exhibited relatively low variability and were consistently associated with improved growth and heartwood yield. The study demonstrates that sandalwood productivity is strongly influenced by the interaction of climatic conditions, soil fertility, and tree growth characteristics. The integration of environmental, edaphic, and growth variables through multivariate analyses provides a robust framework for identifying key drivers of sandalwood performance and offers valuable insights for zonal agroforestry planning, resource allocation, and site-specific management strategies aimed at maximizing heartwood production across Karnataka.

Keywords

Sandalwood, Tree Growth Parameters, Soil Nutrients, Coefficient of Variation, Correlation, Principal Components

1. Introduction

Sandalwood (*Santalum album L.*), commonly referred to as East Indian Sandalwood, holds a prominent position among the most valuable and culturally significant tree species worldwide (Subasinghe et al., 2016). Renowned for its fragrant heartwood and essential oil, sandalwood has been used in India for more than two thousand years in perfumery, traditional medicine, religious ceremonies, and fine woodcraft (Ganeshaiah et al., 2007). Among the 19 recognized species of the genus *Santalum*, *S. album* is distinguished by its high concentration of α- and β-santalol, which confer superior aromatic and commercial qualities compared with other sandalwood species, including Australian sandalwood. India, particularly the state of Karnataka, represents the principal natural habitat of sandalwood and supports more than 70 % of the species' natural population (Srinivasan et al., 1992). However, extensive illegal harvesting, overexploitation, and inadequate regeneration efforts have resulted in a substantial decline in natural sandalwood resources. Consequently, annual production has decreased from approximately 4,000 tonnes in the 1960s to less than 350 tonnes in recent years (Ananthapadmanabha, 2000). The widening gap between supply and demand has significantly increased market prices, making sandalwood one of the most economically valuable tree species globally.

The commercial value of sandalwood is primarily determined by the quantity and quality of heartwood and the essential oil contained within it. Heartwood formation is a gradual biological process influenced by genetic, physiological, environmental, and edaphic factors. Soil fertility, moisture availability, climatic conditions, and tree age play critical roles in determining heartwood development and accumulation. Therefore, understanding the factors affecting heartwood formation is essential for improving plantation productivity and maximizing economic returns. Traditionally, heartwood assessment has relied on destructive methods such as increment boring and stem sampling. Although these techniques provide direct information regarding heartwood content, they can cause physical injury to standing trees and increase the risk of pathogen invasion and structural damage. Consequently, there is increasing interest in adopting non-destructive approaches for evaluating heartwood development in living trees (Divakara & Chaithra, 2022).

Electrical Resistance Tomograph (ERT) has emerged as a promising non-invasive technique for internal tree assessment. The method generates tomographic images based on differences in electrical resistance associated with variations in moisture content and ionic conductivity within the stem (Divakara & Singh, 2025). Because heartwood generally exhibits lower moisture content and distinct electrical properties than sapwood, ERT can effectively delineate heartwood boundaries and estimate heartwood development without damaging the tree. In addition, ERT has proven useful for detecting internal defects and decay, making it a valuable tool for sustainable forest and plantation management (Divakara & Chaithra, 2022).

Despite the economic importance of sandalwood heartwood, limited research has examined the combined influence of tree age, soil fertility, and environmental factors on heartwood formation using non-destructive technologies. A comprehensive understanding of these relationships is essential for developing site-specific management strategies and identifying suitable cultivation environments across diverse agro-climatic regions.

Multivariate statistical techniques provide powerful tools for evaluating complex interactions among environmental and biological variables. Among these, Principal Component Analysis (PCA) has been widely applied in agricultural, forestry, and ecological studies to identify the most influential variables and reduce dataset dimensionality while retaining maximum information (Dunteman, 1989). Previous studies have successfully utilized PCA to evaluate fertilizer-use efficiency and soil fertility dynamics under varying environmental conditions (Norris, 1972; Rao, 1973; Krzanowski, 1979; Jolliffe, 1986). Maruthi Sankar et al. (2014b) demonstrated the utility of PCA in optimizing fertilizer management under different rainfall regimes, whereas Parama et al. (2018b) employed PCA to identify key soil fertility indicators in semi-arid Alfisols. Similarly, Ladoni et al. (2010) used PCA to assess temporal changes in soil organic matter, highlighting its effectiveness in environmental monitoring. Anderson and Furley (1975) further emphasized the analytical and economic benefits of dimensionality reduction when transformed components capture a substantial proportion of the original data variability.

Against this background, the present study employed correlation analysis and Principal Component Analysis (PCA) to investigate the relationships among soil fertility parameters, climatic variables, tree growth characteristics, and heartwood development in *Santalum album* L. across 73 locations distributed among nine agro-climatic zones of Karnataka, India. The specific objectives were to: (i) identify the key environmental and edaphic factors influencing sandalwood growth and heartwood formation; (ii) evaluate the variability and interrelationships among soil fertility parameters; (iii) classify agro-climatic zones based on growth suitability and productivity characteristics; and (iv) provide scientific recommendations for site-specific sandalwood cultivation and management. The findings are expected to contribute to sustainable sandalwood production, improved resource allocation, and enhanced understanding of the ecological factors governing heartwood development under diverse agro-climatic conditions.

2. 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 **Table 1** and **Table 2**, and **Figure 1**) were established on farmers' lands. Plot sizes varied from 110 m^2 to 533 m^2, 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 district wise 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.

Agro-climatic zones (ACZ)	Districts/places	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, Hiriyur, Hosadurga, Holalkere, Jagalur, Molkalmuru, Kadur, Madhugiri, Pavagada, C. N. Halli, Sira	**13**

Continued

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 in percentage. 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.

Table 2. Locational details of sample plots selected for collection of ERT heartwood data.

Plot No	District	Taluk	Place	Latitude	Longitude	Altitude	Age
1	Chikmangalore	Tarikere	Doranalu	N 13˚15'29.2"	E 75˚49'47.45"	680	12
2	Chikmangalore	Tarikere	Bellanahalli	N 13˚40'36.3"	E 75˚50'17.8"	733	9
3	Chikmangalore	Tarikere	Aliyoor	N 13˚44'43.6"	E 75˚46'32.3"	669	10
4	Chikmangalore	Tarikere	Bettadahalli	N 13˚42'36"	E 75˚50'44.8"	708	15
5	Chikmangalore	Kadur	Channapura	N 13˚55'51.2"	E 75˚34'20.3"	603	10
6	Shimogha	Shikaripura	Aliyur	N 13˚41'47"	E 75˚52'51.9"	750	11
7	Shimogha	Shimogha	Sutkote	N 14˚02'39.1"	E 75˚36'50.7"	656	15
8	Shimogha	Shimogha	Sutkote	N 14˚02'39.1"	E 75˚36'50.7"	656	15
9	Hassan	Arkalgudu	Daddamage	N 12˚45'49.94"	E 76˚3'26.54"	918	10
10	Hassan	Arkalgudu	Daddamage	N 12˚45'49.94"	E 76˚3'26.54"	918	8
11	Davangare	Honnahalli	Yaragalan	N 14˚9'29.87"	E 75˚32'38.23"	631	17
12	Davangare	Nyamati	Mussenalu	N 14˚8'55.09"	E 75˚32'22.55"	657	13
13	Havare	Rannibenur	Aremallapur	N 14˚38'14.77"	E 75˚45'31.06"	583	11

Continued

14	Havare	Rannibenur	Medleri	N 14˚40'1.5"	E 75˚43'55.2"	600	15
15	Udupi	Karkala	Jarkala	N 13˚16'26.4"	E 74˚56'34.8"	80	13
16	Udupi	Karkala	Jarkala	N 13˚16'26.4"	E 74˚56'34.8"	80	10
17	Chitradurga	Hosadurga	Nagenahalli	N 13˚49'36.84"	E 76˚14'21.48"	765	6
18	Chitradurga	Hosadurga	Madhure	N 13˚49'45.48"	E 76˚13'46.92"	765	7
19	Chitradurga	Chitradurga	Alaghatta	N 13˚41'15.72"	E 76˚ 13' 33.6"	774	9
20	Chitradurga	Hosadurga	Ballalasamudra	N 13˚42'11.06"	E 76˚17'8.88"	765	8
21	Chitradurga	Hosadurga	Besanahalli	N 13˚40'50.16"	E 76˚17'15.36"	765	7
22	Chitradurga	Holalkere	Upparigenahalli	N 13˚59'29.76"	E 76˚21'43.92"	661	12
23	Chitradurga	Hosadurga	Hullukatte	N 13˚52'34.32"	E 76˚20'48.84"	713	8
24	Chitradurga	Chellakere	Hulikunte	N 14˚8'8.3"	E 76˚44'37.32"	764	13
25	Bangalore rural	Hoskote	Agasarahalli	N 12˚59'20.83"	E 76˚4'23.05"	939	11
26	Bangalore rural	Hoskote	Pulaganahalli	N 13˚7'56.24"	E 77˚53'18.31"	866	10
27	Bangalore rural	Dodballapura	Madhapura	N 13˚18'18.86"	E 77˚30'45.54"	885	10
28	Bangalore rural	Nelamangala	Hanchipura	N 13˚18'45"	E 77˚13'16.14"	874	7
29	Bangalore rural	Nelamangala	Budihal	N 13˚7'56.36"	E 77˚21'36.04"	881	7
30	Kolar	Malur	Kenchapura	N 13˚1'47.82"	E 78˚4'41.38"	878	13
31	Kolar	Kolar	Shipandipura	N 13˚4'56.50"	E 78˚10'39.65"	854	10
32	Kolar	Srinivaspur	Yeldur—plot 1	N 13˚17'26.77"	E 78˚10'49.15"	841	9
33	Kolar	Srinivaspur	Yeldur—plot 2	N 13˚17'26.77"	E 78˚16'48.61"	841	9
34	Kolar	Srinivaspur	Yeldur—plot 3	N 13˚5'58.16"	E 78˚8'44.02"	853	9
35	Kolar	Srinivaspur	Kolaturu	N 13˚16'4.04"	E 78˚17'35.63"	876	12
36	Kolar	Srinivaspur	Kolaturu	N 13˚15'32.90"	E 78˚17'30.3"	826	11
37	Kolar	Srinivaspur	Attikunte	N 13˚15'32.94"	E 78˚17'30.37"	825	13
38	Kolar	Srinivaspur	Hogalgere	N 13˚19'26.47"	E 78˚19'14.45"	839	7
39	Kolar	Srinivaspur	Srinivaspur	N 13˚27'7"	E 78˚15'9"	819	11
40	Kolar	Srinivaspur	Thernahalli	N 13˚17'42"	E 78˚6'58"	821	10
41	Chikballapur	Chintamani	Hiranyapalli	N 13˚24'28"	E 78˚6'12"	879	11
42	Chikballapur	Chintamani	Bukkanahalli	N 13˚25'17"	E 78˚4'5"	879	9
43	Chikballapur	Chintamani	Kuruburu	N 13˚11'7.44"	E 78˚26'24"	865	7
44	Chikballapur	Gauribidanur	Nakkalahalli	N 13˚41'2.76"	E 77˚35'36.6"	684	6
45	Chikballapur	Chintamani	Chowdenahalli	N 13˚9'7.2"	E 78˚0'3.6"	879	12
46	Chikballapur	Gauribidanur	Bevinahalli	N 13˚29'49.45"	E 77˚28'54.41"	728	10
47	Chikballapur	Gauribidanur	Kodigehalli	N 13˚29'48.84"	E 77˚28'53.69"	727	8
48	Tumkur	Sira	Baragur	N 13˚57'42.66"	E 76˚19'56.24"	625	5
49	Tumkur	Tumkur	Sirivara	N 13˚13'26.41"	E 77˚0'17.48"	832	8
50	Tumkur	Madhugiri	ID halli	N 13˚49'30.51"	E 77˚20'35.06"	678	17

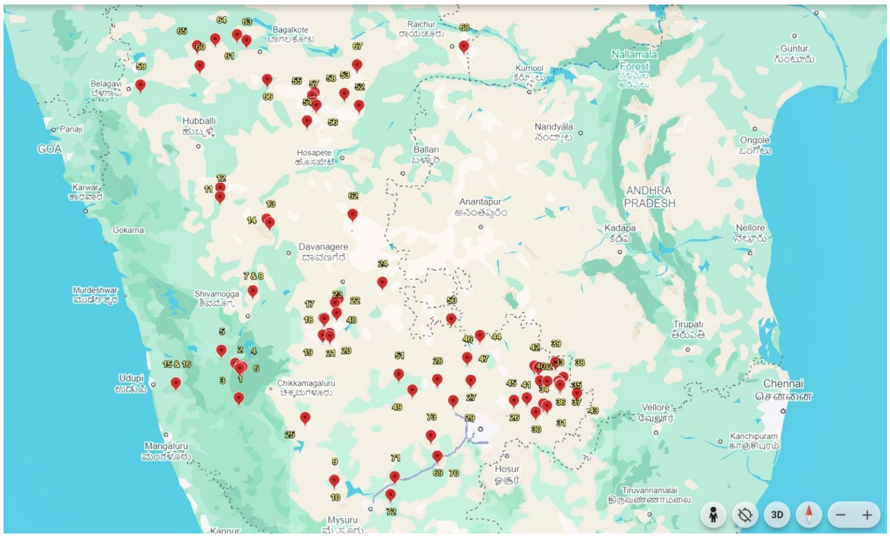
Continued

51	Tumkur	Gubbi	Thippur	N 13˚21'26.6"	E 76˚53'9.67"	828	13
52	Koppal	Gangawati	Adapura	N 15˚37'50.16"	E 76˚32'22.66"	293	12
53	Koppal	Kushtagi	Menedal	N 15˚43'54.32"	E 76˚24'33.69"	514	11
54	Koppal	Yalburga	Shirur	N 15˚29'58.52"	E 76˚4'56.49"	538	12
55	Koppal	Kushtagi	Yelburthi	N 15˚42'46.43"	E 76˚7'34.85"	643	10
56	Koppal	Yalburga	Tharlkatti	N 15˚37'59.82"	E 76˚9'49.82"	563	10
57	Koppal	Yalburga	Mandalmari	N 15˚39'18.87"	E 76˚8'18.3"	681	10
58	Koppal	Kushtagi	Madlegatte	N 15˚44'13.66"	E 76˚8'50.88"	687	10
59	Belgaum	Belgaum	Tarihal	N 15˚48'4.92"	E 74˚36'21.31"	752	7
60	Belgaum	Ramdurga	Katkol	N 15˚58'3.89"	E 75˚7'53.18"	578	10
61	Belgaum	Ramdurga	Kamkeri	N 16˚11'49.47"	E 75˚15'55.48"	569	6
62	Bellary	Kudlige	C. J. Halli tanda	N 14˚42'32.37"	E 76˚29'4.6"	658	17
63	Bagalkot	Bagalkot	Tulasigeri	N 16˚11'2.4"	E 75˚32'34.8"	541	9
64	Bagalkot	Bagalkot	Udagatti	N 16˚13'58.3"	E 75˚27'30.29"	541	13
65	Belguam	Ramdurga	Bhagojikoppa	N 16˚8'16.8"	E 75˚6'21.59"	578	15
66	Gadag	Rona	Holehadagali	N 15˚51'3.6"	E 75˚43'48"	596	12
67	Raichur	Lingsugur	Mudaldinni	N 15˚58'33.6"	E 76˚31'15.6"	508	7
68	Raichur	Raichur	Undral Doddi	N 16˚8'6"	E 77˚27'50.39"	404	7
69	Ramanagara	Channapatnna	Keramaga-ladoddi	N 12˚39'50.4"	E 77˚13'19.2"	692	8
70	Ramanagara	Channapatnna	Keramaga-ladoddi	N 12˚39'43.2"	E 77˚13'19.2"	692	8
71	Mandya	Mandya	Hullukere	N 12˚29'13.2"	E 76˚51'3.59"	798	9
72	Mysore	T. Narasipura	Madegow-dana-hundi	N 12˚20'2.4"	E 76˚48'54.0"	703	7
73	Ramanagara	Magadi	S. Bydarahalli	N 12˚50'09.6"	E 77˚09'56.8"	773	8

2.1. Electrical Resistance Tomograph (ERT) in Sandalwood Heartwood Estimation

To assess heartwood formation and quantify heartwood content in standing sandalwood (*Santalum album* L.) trees, Electrical Resistance Tomograph (ERT) was employed as a non-destructive diagnostic technique (Divakara et al., 2020). Electrical Resistance Tomography (ERT) is a non-destructive imaging technique widely used to evaluate the internal structure of standing trees and estimate heartwood content without causing damage. The technique operates by injecting a low-intensity electrical current through a series of electrodes placed around the circumference of the tree stem and measuring the resulting voltage differences. These measurements are processed using specialized software to reconstruct cross-sectional images, known as tomograms that represent the electrical resistivity distribution within the stem.

The electrical resistivity of wood is influenced primarily by moisture content, electrolyte concentration, and wood density. Regions with higher moisture and ionic content generally exhibit lower resistivity, whereas drier and denser tissues show higher resistivity. Since sapwood contains physiologically active cells with relatively high moisture content, it typically displays lower electrical resistance. In contrast, heartwood consists of older, non-living cells enriched with extractives and characterized by lower moisture content, resulting in higher electrical resistance. These differences create distinct resistivity patterns that enable the clear differentiation of sapwood and heartwood zones within the stem.



(Locational details of the sample plots are in Table 2).

Figure 1. Distribution map of sample plots.

In ERT tomograms, resistivity variations are represented using colour gradients, commonly ranging from blue (low resistivity, high moisture content) to brown (high resistivity, low moisture content). The sharp contrast between sapwood and heartwood allows accurate estimation of heartwood dimensions and volume. In addition to heartwood assessment, ERT can identify internal defects such as decay, cavities, hollowness, and zones of mechanical stress, thereby providing valuable information on overall tree health.

Electrical Resistance Tomograph (ERT)

The application of ERT in tropical forestry has been pioneered by the Institute of Wood Science and Technology (IWST), Bengaluru, particularly for economically important species such as *Santalum album* (Indian sandalwood). Because sandalwood value is directly linked to heartwood quantity and quality, ERT offers a practical and sustainable alternative to destructive methods such as increment boring. The technology enables repeated monitoring of heartwood development over time without compromising tree growth or increasing susceptibility to infection.

However, the interpretation of ERT images is species-specific because electrical resistivity patterns vary according to wood anatomy, moisture distribution, and chemical composition. Consequently, calibration and validation are necessary for each species to ensure accurate assessment. Despite these considerations, ERT has emerged as a powerful diagnostic tool for forestry research and plantation management, providing rapid, reliable, and environmentally sustainable information on heartwood formation, internal defects, and tree condition. Its application supports precision Silviculture, resource valuation, and informed decision-making in high-value timber and sandalwood plantations.

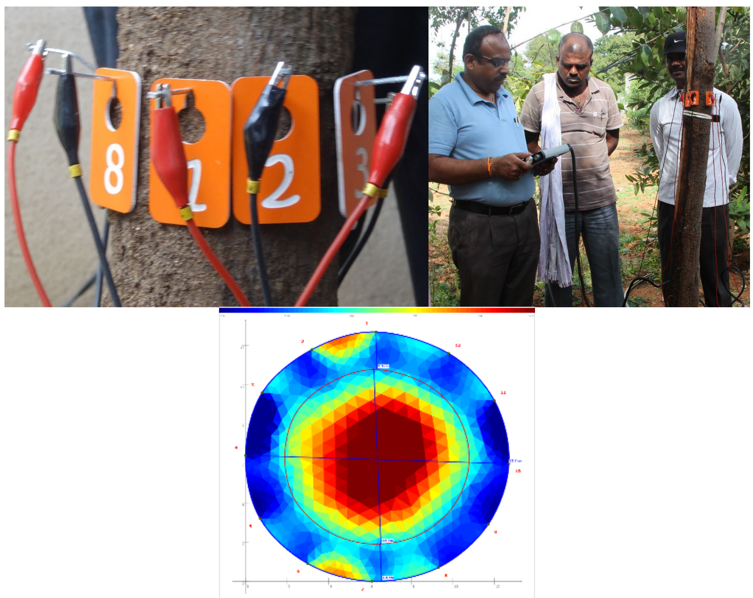


Image capturing using Electrical Resistance Tomograph (ERT)

2.1.1. Capturing of ERT Images from Standing Trees

- Measurement of Tree Girth: The process begins by measuring the girth of the sandalwood tree at a standardized height, commonly at breast height (1.37 meters from the ground). This girth measurement is essential for determining the number and placement of electrodes.
- Installation of Electrodes: Based on the recorded girth, metallic nails (serving as Measuring Points, or MPs) are evenly hammered around the circumference of the tree trunk. These act as contact points for electrical current conduction. The number of nails varies with the tree's girth, typically ranging from a min-

imum of 8 to a maximum of 24.

- Sensor Configuration: Multi-electrode sensor cables from the ERT device (TreeTronic 3) are then clipped securely onto each of the nails to complete the circuit.
- Data Entry: Essential information including the number of measuring points (MPs), tree girth/circumference, and other relevant tree-specific details are input into the device's interface.
- Scanning and Data Acquisition: Once setup is complete, the ERT device sequentially scans each measuring point, and a real-time graphical output is displayed on the instrument's screen.
- Data Storage: The scanned tomogram and associated data are saved automatically to the internal SD memory of the TreeTronic 3 device. The device has the capacity to store up to 120 scan files.

2.1.2. Analysis of ERT Images for Heartwood Estimation

- Image Transfer and Visualization: The tomographic image captured by the TreeTronic 3 device is transferred to a PC or laptop equipped with PiCUS TreeTronic software for further visualization and analysis.
- 2D Tomographic Interpretation: The software generates a two-dimensional cross-sectional image of the scanned trunk segment. This image displays color variations ranging from blue (indicating low electrical resistance) to brown (indicating high resistance), which help visualize the internal structure of the tree.
- 3D Visualization: A three-dimensional reconstruction is also available, offering a comprehensive understanding of the spatial distribution of sapwood and heartwood along the length of the stem. This view also reveals resistivity variation across different trunk segments.
- Diagnostic Interpretation: Based on color-coded resistivity patterns, the tomogram can be analyzed to detect and distinguish various internal features such as: Presence and extent of heartwood and sapwood, Clear heartwood-sapwood boundary, Areas of decay or hollowness, if present.
- Resolution and Accuracy: Each image provides a high-resolution, detailed snapshot of the internal condition of the tree at the measured section. This allows for precise and non-invasive assessment.
- Effective Analysis Criteria: Accurate interpretation of ERT images is facilitated when distinct colour separations based on resistivity patterns are clearly visible, allowing reliable assessment of heartwood formation and structural integrity as follows;

Brown	This indicates higher resistance because of low moisture content
Red	This indicates high resistance, comparitively less than the brown color
Yellow	Indicates medium resistance because of slight moisture content
Light blue	Indicates sapwood with low resistance because of moderate water content
Blue	Indicates sapwood with low resistance because of high water content

2.2. Statistical Analysis

Descriptive statistics viz., mean, standard deviation and coefficient of variation (%) were derived for each parameter. Relationships among soil and tree parameters were determined and tested for significance. Estimates of correlation between soil parameters are derived in order to assess the superiority and usefulness of variables for modelling the soil fertility variation in farmers' fields (Gomez & Gomez, 1984). The primary objective of the study was to evaluate the variability in soil fertility parameters and identify the variables contributing most significantly to this variability using Principal Component Analysis (PCA). PCA was employed to reduce the dimensionality of the dataset and to extract key components that account for maximum variance in the soil and tree parameter data. Relationships among soil and tree growth variables were examined using Karl Pearson's correlation coefficients, and statistical significance was tested following the procedures outlined by Gomez and Gomez (1984). These correlations were further utilized to determine the most influential variables for inclusion in the PCA, aiding in the modelling of soil fertility dynamics in farmers' fields across different agro-climatic zones and over time.

Principal Component Analysis

Based on the procedure described by Dunteman George (1989), Jolliffe (1986) and Krzanowski (1979), the principal components (PC) for explaining the variability of soil parameters were determined. Based on the PC model, the principal components could be postulated as

$$\begin{aligned} P_1 &= a_{11}X_1 + a_{12}X_2 + \cdots + a_{1k}X_k \\ P_2 &= a_{21}X_1 + a_{22}X_2 + \cdots + a_{2k}X_k \\ &\cdots \\ P_k &= a_{k1}X_1 + a_{k2}X_2 + \cdots + a_{kk}X_k \end{aligned} \tag{1}$$

In Equation (2), aij are loadings of variables on "Pi", which are chosen such that they satisfy two conditions, viz., (i) PCs are orthogonal with respect to each other; and (ii) 1st PC, say PC-1 will explain maximum variance of the variables; 2nd PC will explain maximum of the remaining variance in variables after eliminating the variance explained by 1st PC and so on. An eigen value "λk" indicates the variance extracted by the kth PC and can be expressed as percentage of total variance of all components, i.e., Pk = (λk/k) × 100. The computational procedure of 1st PC is repeated for the 2nd PC and all subsequent PCs. The 1st PC would always have a higher eigen value than the 2nd PC; the 2nd PC has a higher eigen value than the 3rd PC and so on. Based on the analysis, we can assess the usefulness of a PC model by identifying (i) significant number of PCs with eigen value of more than "1" to extract maximum variance in the data; (ii) soil parameters which have a loading of more than +0.60 or less than −0.60 on significant PCs; and (iii) percent of variance explained by each significant PC.

Based on CV (%) and loadings of parameters on PCs under different ACZs, parameters were grouped into 4 quadrangles viz., (i) Q1 representing negative loadings on PCs with low CV; (ii) Q2 representing positive loadings on PCs with low CV; (iii) Q3 representing negative loadings on PCs with high CV; and (iv) Q4 representing positive loadings on PCs with high CV. Out of the 4 quadrangles, the soil parameters occurring in Q2 would be important and carry greater influence on the tree parameters since they have relatively low CV and positive loadings on different PCs.

3. Results and Discussion

3.1. Relationship between Rainfall, Temperature and Tree Parameters under Different ACZs

In Agro-Climatic Zone 3 (ACZ-3), comprising 15 locations, a strong and significant negative correlation (r = −0.966) was observed between annual rainfall and annual temperature (**Table 3**). In ACZ-5, which included 27 locations, a significant positive correlation (r = 0.396) was found between annual rainfall and heartwood development. When data from ACZ-2, 7, 8, 9, and 10 were pooled (10 locations in total), a significant positive correlation (r = 0.667) was observed between rainfall and heartwood yield in sandalwood trees. However, across all 73 locations encompassing the 9 ACZs, a significant negative correlation (r = −0.297) was recorded between rainfall and tree height parameters. Additionally, temperature exhibited a significant negative correlation with several heartwood traits: (i) heartwood yield in ACZ-5 (r = −0.483), (ii) heartwood diameter in ACZ-6 (r = −0.730), and (iii) both heartwood diameter (r = −0.283) and heartwood yield (r = −0.235) when pooled data from all 73 locations were considered (**Table 3**).

Table 3. Relationship of tree parameters with annual rainfall and temperature under different ACZs.

Parameter-1	Parameter-2	ACZ-3 (15)	ACZ-4 (13)	ACZ-5 (27)	ACZ-6 (8)	ACZ-2, 7, 8, 9, 10 (10)	Pooled (73)
Rainfall	Temperature	−0.966**	−0.327	0.280	−0.436	−0.141	−0.051
	Tree height	−0.496	0.177	−0.271	0.109	−0.493	−0.297*
	Tree diameter	0.086	0.146	0.188	0.491	−0.570	−0.159
	HWD	0.085	−0.222	0.269	0.534	−0.018	0.048
	Heartwood	−0.052	−0.334	0.396*	0.004	0.667*	0.103
Temperature	Tree height	0.486	−0.255	0.165	0.522	0.131	0.214
	Tree diameter	−0.073	−0.048	−0.008	0.402	−0.170	0.154
	HWD	−0.039	0.202	−0.235	−0.730*	−0.258	−0.283*
	Heartwood	−0.109	0.095	−0.483*	−0.008	0.043	−0.235*

*and ** indicate significance at 5% and 1% level of significance respectively; HWD: Heartwood diameter (cm) ACZ: Agro-climatic zone; Values in parentheses indicate number of locations. Critical correlation values with 6 degrees of freedom at 5% level = 0.707 and 1% level = 0.834. Critical correlation values with 8 degrees of freedom at 5% level = 0.632 and 1% level = 0.765. Critical correlation values with 11 degrees of freedom at 5% level = 0.553 and 1 % level = 0.684. Critical correlation values with 13 degrees of freedom at 5% level = 0.514 and 1% level = 0.641. Critical correlation values with 25 degrees of freedom at 5% level = 0.381 and 1% level = 0.487. Critical correlation values with 71 degrees of freedom at 5% level = 0.232 and 1% level = 0.302.

3.2. Relationships between Soil and Tree Parameters under Different ACZs

Correlation values were tested for significance at 5% and 1% levels, with degrees of freedom based on the number of locations under each Agro-Climatic Zone (ACZ). The analysis revealed the following significant relationships (Table 4).

Across ACZ-3, ACZ-4, ACZ-5, ACZ-6, and pooled data from ACZ-2, 7, 8, 9, and 10, Organic Carbon (OC) showed a significant positive correlation with Nitrogen (N); Heartwood exhibited a significant correlation with tree diameter. Tree height correlated significantly with S (ACZ-3, 6, pooled), tree age (ACZ-6, pooled), OC, N, Zn (ACZ-3), and K (ACZ-5). Tree diameter had significant correlation with pH (ACZ-5, 6). Heartwood was significantly related to tree height, heartwood diameter (HWD) (ACZ-4), and tree age (ACZ-3, 5, pooled). Tree age also had significant correlations with HWD (ACZ-4) and Fe (ACZ-6).

Calcium (Ca) was significantly correlated with Magnesium (Mg) (ACZ-3, 4, 5) and Sulphur (S) (ACZ-3, 5, pooled zones) and Electrical Conductivity (EC) was significantly related to Ca (ACZ-3, 6, pooled), pH (ACZ-3, 4, pooled), and **S** (ACZ-4, pooled). EC also showed a significant correlation with Phosphorus (P) under ACZ-5. Soil pH showed significant correlations with Ca and Cu (ACZ-3, pooled), S (ACZ-3, 5), Fe, P, Zn (ACZ-3) and Mg (ACZ-5). Other Key Correlations include Sulphur (S) correlated with N, OC, Zn (ACZ-3, 4), and with Cu, Fe (ACZ-3). Phosphorus (P) showed significant relationships with S, Cu, and Fe (ACZ-3, 5, 6). Magnesium (Mg) correlated significantly with Cu (ACZ-3) and Zn (ACZ-4). Iron (Fe) was significantly correlated with HWD (ACZ-5).

Table 4. Estimates of correlation between different soil and tree parameters under different ACZs.

Parameter-1	Parameter-2	ACZ-3 (15)	ACZ-4 (13)	ACZ-5 (27)	ACZ-6 (8)	ACZ-2, 7, 8, 9, 10 (10)	Pooled (73)
Tree age	Soil pH	−0.306	0.266	−0.148	0.570	−0.641*	−0.149
Tree age	EC	−0.279	0.185	−0.128	0.107	−0.574	−0.150
Tree age	Organic Carbon	0.287	0.017	−0.194	0.491	−0.225	0.052
Tree age	Nitrogen	0.530*	−0.078	−0.123	0.491	−0.225	0.094
Tree age	Phosphorus	0.001	−0.130	−0.135	0.788*	−0.555	−0.141
Tree age	Potassium	−0.431	−0.336	−0.173	−0.184	−0.184	−0.312**
Tree age	Calcium	−0.196	0.106	−0.197	0.067	−0.802**	−0.033
Tree age	Magnesium	0.143	0.182	−0.274	0.578	−0.044	0.119
Tree age	Sulphur	0.081	0.406	−0.296	0.474	−0.922**	−0.036
Tree age	Iron	−0.097	−0.130	−0.260	−0.809*	−0.156	−0.234*
Tree age	Manganese	−0.083	0.523	−0.158	0.111	−0.535	0.056
Tree age	Zinc	−0.293	0.253	−0.298	−0.485	0.147	−0.086
Tree age	Copper	0.117	−0.520	0.045	−0.057	−0.519	−0.237*
Tree age	Tree height	−0.217	0.283	0.252	0.761*	0.882**	0.241*

Continued

Tree age	Tree diameter	0.231	0.477	0.084	0.283	0.433	0.321**
Tree age	HWD	0.252	0.704**	0.305	0.324	0.596	0.470**
Tree age	Heart wood	0.019	0.752**	0.400*	0.380	0.662*	0.477**
Soil pH	EC	0.630*	0.600*	0.183	0.159	0.640*	0.499**
Soil pH	Organic Carbon	0.505	0.281	0.258	0.536	−0.047	0.296*
Soil pH	Nitrogen	0.354	0.304	0.243	0.535	−0.047	0.240*
Soil pH	Phosphorus	0.757**	−0.121	0.226	0.600	0.517	0.366**
Soil pH	Potassium	−0.282	0.369	0.051	−0.163	0.744*	0.002
Soil pH	Calcium	0.615*	−0.164	0.155	−0.227	0.633*	0.452**
Soil pH	Magnesium	0.383	−0.014	0.418*	0.671	−0.028	0.297*
Soil pH	Sulphur	0.796**	0.248	0.484*	0.293	0.587	0.619**
Soil pH	Iron	−0.688**	−0.434	−0.296	−0.410	−0.451	−0.338**
Soil pH	Manganese	0.309	−0.149	−0.086	0.164	0.146	0.009
Soil pH	Zinc	0.627*	−0.033	0.090	−0.436	−0.138	0.249*
Soil pH	Copper	−0.721**	0.010	−0.007	−0.244	0.692*	−0.063
Soil pH	Tree height	−0.712**	0.249	0.223	0.580	−0.596	−0.231
Soil pH	Tree diameter	0.037	−0.386	0.408*	0.812*	−0.348	0.112
Soil pH	HWD	0.037	−0.103	0.156	0.805*	−0.449	0.037
Soil pH	Heart wood	−0.137	0.200	−0.301	−0.306	−0.423	−0.167
EC	Organic Carbon	0.403	0.352	−0.125	−0.390	−0.249	0.134
EC	Nitrogen	0.126	0.390	−0.078	−0.390	−0.249	0.094
EC	Phosphorus	0.334	−0.072	0.447*	0.041	0.571	0.341**
EC	Potassium	−0.210	0.342	−0.147	−0.236	0.573	−0.036
EC	Calcium	0.808**	−0.079	0.184	0.754*	0.833**	0.512**
EC	Magnesium	0.424	0.193	0.224	0.448	0.159	0.297*
EC	Sulphur	0.406	0.684**	0.064	−0.264	0.636*	0.528**
EC	Iron	−0.374	−0.267	0.321	0.209	−0.100	−0.105
EC	Manganese	0.393	−0.251	0.529**	−0.190	0.257	0.001
EC	Zinc	0.118	0.363	−0.165	−0.436	0.055	0.144
EC	Copper	−0.521*	0.054	−0.165	0.467	0.492	−0.058
EC	Tree height	−0.316	0.087	0.224	−0.029	−0.695*	−0.235*
EC	Tree diameter	−0.134	−0.388	−0.088	0.153	−0.272	−0.083
EC	HWD	0.073	−0.168	−0.211	0.155	−0.366	−0.091
EC	Heart wood	0.408	0.118	−0.276	0.068	−0.286	−0.042
Organic Carbon	Nitrogen	0.906**	0.961**	0.964**	0.990**	0.991**	0.968**
Organic Carbon	Phosphorus	0.682**	−0.098	0.042	0.381	0.074	0.137
Organic Carbon	Potassium	−0.391	−0.171	0.218	0.454	−0.331	−0.202

Continued

Organic Carbon	Calcium	0.500	−0.075	0.053	−0.426	−0.191	0.158
Organic Carbon	Magnesium	0.454	0.442	0.248	0.026	−0.604	0.126
Organic Carbon	Sulphur	0.730**	0.602*	0.093	0.167	0.098	0.400**
Organic Carbon	Iron	−0.406	0.044	−0.091	−0.544	0.394	−0.181
Organic Carbon	Manganese	0.003	−0.222	0.081	0.181	0.522	−0.050
Organic Carbon	Zinc	0.409	0.399	0.083	−0.486	−0.488	0.138
Organic Carbon	Copper	−0.380	−0.111	0.048	−0.630	−0.074	−0.176
Organic Carbon	Tree height	−0.723**	−0.536	−0.073	0.550	−0.156	−0.306*
Organic Carbon	Tree diameter	0.142	0.028	0.328	0.445	−0.488	−0.022
Organic Carbon	HWD	0.239	−0.086	0.201	0.518	−0.452	−0.039
Organic Carbon	Heart wood	0.074	−0.164	−0.119	0.362	−0.002	−0.068
Nitrogen	Phosphorus	0.615*	−0.108	0.029	0.381	0.074	0.118
Nitrogen	Potassium	−0.457	−0.146	0.263	0.455	−0.331	−0.195
Nitrogen	Calcium	0.194	−0.118	0.061	−0.426	−0.191	0.034
Nitrogen	Magnesium	0.413	0.407	0.240	0.026	−0.604	0.105
Nitrogen	Sulphur	0.688**	0.592*	0.105	0.167	0.098	0.373**
Nitrogen	Iron	−0.351	0.068	−0.078	−0.544	0.394	−0.163
Nitrogen	Manganese	−0.075	−0.229	0.119	0.181	0.522	−0.040
Nitrogen	Zinc	0.264	0.447	−0.176	−0.486	−0.488	0.006
Nitrogen	Copper	−0.298	−0.020	0.093	−0.630	−0.074	−0.144
Nitrogen	Tree height	−0.721**	−0.442	−0.020	0.550	−0.156	−0.265*
Nitrogen	Tree diameter	0.159	−0.162	0.251	0.445	−0.488	−0.064
Nitrogen	HWD	0.228	−0.229	0.099	0.517	−0.452	−0.095
Nitrogen	Heart wood	0.014	−0.215	−0.200	0.362	−0.002	−0.114
Phosphorus	Potassium	−0.387	0.065	0.083	−0.250	0.182	0.020
Phosphorus	Calcium	0.545*	−0.391	−0.065	−0.294	0.509	0.166
Phosphorus	Magnesium	0.379	−0.006	0.122	0.318	0.125	0.180
Phosphorus	Sulphur	0.964**	−0.109	0.246	0.670	0.743*	0.405**
Phosphorus	Iron	−0.503	0.013	0.423*	−0.798*	−0.224	0.060
Phosphorus	Manganese	0.331	0.399	0.223	0.451	0.426	0.318*
Phosphorus	Zinc	0.649**	−0.193	0.088	−0.193	−0.146	0.105
Phosphorus	Copper	−0.599*	−0.259	−0.020	0.164	0.863**	−0.047
Phosphorus	Tree height	−0.859**	0.228	0.339	0.713*	−0.502	−0.034
Phosphorus	Tree diameter	−0.039	0.049	−0.069	0.554	0.031	0.023
Phosphorus	HWD	−0.048	0.017	−0.210	0.562	−0.069	−0.053
Phosphorus	Heart wood	−0.151	−0.058	−0.281	0.035	−0.258	−0.185
Potassium	Calcium	−0.223	0.154	−0.422	−0.152	0.423	−0.139

Continued

Potassium	Magnesium	−0.296	−0.108	−0.286	−0.382	0.272	−0.103
Potassium	Sulphur	−0.397	−0.149	−0.361	−0.386	0.160	−0.308*
Potassium	Iron	0.383	−0.443	−0.327	0.323	−0.383	−0.073
Potassium	Manganese	−0.102	−0.291	0.204	−0.220	−0.372	−0.003
Potassium	Zinc	0.038	−0.276	−0.246	−0.505	0.019	−0.174
Potassium	Copper	0.342	0.271	0.294	−0.085	0.360	0.340**
Potassium	Tree height	0.245	0.179	0.612**	0.094	−0.402	0.309*
Potassium	Tree diameter	−0.132	−0.468	0.019	0.210	−0.286	−0.098
Potassium	HWD	−0.340	−0.260	−0.210	0.278	−0.234	−0.166
Potassium	Heart wood	−0.435	−0.009	−0.381*	0.362	0.160	−0.201
Calcium	Magnesium	0.575*	0.698**	0.761**	0.411	0.223	0.360**
Calcium	Sulphur	0.526*	0.155	0.631**	−0.580	0.791**	0.565**
Calcium	Iron	−0.415	−0.405	0.171	0.228	0.041	−0.147
Calcium	Manganese	0.223	−0.021	−0.371	−0.213	0.435	−0.136
Calcium	Zinc	0.208	0.348	0.126	−0.291	0.085	0.218
Calcium	Copper	−0.474	−0.276	−0.346	0.388	0.552	−0.142
Calcium	Tree height	−0.486	0.224	−0.428*	−0.341	−0.816**	−0.295**
Calcium	Tree diameter	−0.079	0.188	−0.174	−0.357	−0.362	0.115
Calcium	HWD	0.045	0.308	−0.034	−0.339	−0.481	0.169
Calcium	Heart wood	0.171	0.353	0.194	0.361	−0.429	0.155
Magnesium	Sulphur	0.476	0.610*	0.752**	−0.050	0.236	0.425**
Magnesium	Iron	−0.430	−0.457	−0.004	−0.191	−0.042	−0.259*
Magnesium	Manganese	−0.110	0.000	−0.247	−0.035	−0.548	−0.049
Magnesium	Zinc	−0.064	0.710**	0.160	−0.376	0.551	0.279*
Magnesium	Copper	−0.540*	−0.492	−0.345	0.145	0.125	−0.304**
Magnesium	Tree height	−0.594*	0.115	−0.206	0.256	−0.294	−0.121
Magnesium	Tree diameter	−0.146	0.176	0.086	0.363	0.149	0.161
Magnesium	HWD	0.191	0.286	0.093	0.336	0.189	0.196
Magnesium	Heart wood	−0.012	0.324	0.037	−0.218	0.236	0.140
Sulphur	Iron	−0.581*	−0.279	0.128	−0.596	0.124	−0.235*
Sulphur	Manganese	0.382	−0.137	−0.326	−0.007	0.452	−0.135
Sulphur	Zinc	0.615*	0.850**	0.131	0.121	−0.103	0.341**
Sulphur	Copper	−0.708**	−0.333	−0.217	−0.180	0.616	−0.265*
Sulphur	Tree height	−0.935**	−0.074	−0.349	0.714*	−0.874**	−0.499**
Sulphur	Tree diameter	−0.069	0.012	0.085	0.151	−0.216	0.073
Sulphur	HWD	−0.070	0.162	0.036	0.139	−0.373	0.060
Sulphur	Heart wood	−0.139	0.293	−0.048	−0.083	−0.544	−0.010

Continued

Iron	Manganese	−0.151	0.390	0.113	−0.496	0.151	0.264*
Iron	Zinc	−0.238	−0.376	0.003	0.036	−0.429	−0.156
Iron	Copper	0.424	0.082	0.120	0.246	−0.559	0.237*
Iron	Tree height	0.618*	−0.386	−0.171	−0.546	−0.275	−0.054
Iron	Tree diameter	−0.114	0.127	−0.487**	−0.121	−0.051	−0.146
Iron	HWD	0.019	−0.226	−0.463*	−0.155	0.001	−0.233*
Iron	Heart wood	0.366	−0.484	−0.160	−0.348	0.194	−0.244*
Manganese	Zinc	0.219	−0.212	−0.196	0.423	−0.187	−0.131
Manganese	Copper	−0.535*	−0.549	0.327	0.176	0.386	−0.029
Manganese	Tree height	−0.212	0.405	0.202	−0.234	−0.286	0.146
Manganese	Tree diameter	−0.564*	0.367	−0.055	0.230	−0.351	−0.023
Manganese	HWD	−0.491	0.418	−0.114	0.213	−0.474	0.013
Manganese	Heart wood	0.225	0.361	−0.114	−0.137	−0.491	0.063
Zinc	Copper	−0.374	−0.315	−0.206	0.073	0.073	−0.227
Zinc	Tree height	−0.530*	−0.007	−0.291	−0.584	0.059	−0.280*
Zinc	Tree diameter	0.126	−0.042	0.238	−0.450	−0.207	0.087
Zinc	HWD	0.059	0.120	0.368	−0.525	−0.208	0.156
Zinc	Heart wood	−0.282	0.272	0.355	−0.454	−0.034	0.204
Copper	Tree height	0.636*	−0.134	0.239	−0.201	−0.398	0.099
Copper	Tree diameter	0.220	−0.186	−0.172	0.086	−0.105	−0.128
Copper	HWD	0.190	−0.272	−0.141	0.048	−0.203	−0.173
Copper	Heart wood	−0.026	−0.280	−0.004	−0.169	−0.319	−0.148
No. of trees	Tree height	0.294	0.513	0.051	−0.067	0.335	0.195
No. of trees	Tree diameter	−0.491	−0.621*	−0.125	0.009	−0.258	−0.241*
No. of trees	HWD	−0.395	−0.439	0.151	0.067	−0.295	−0.127
No. of trees	Heart wood	0.211	−0.135	0.418*	0.559	−0.261	0.157
Tree height	Tree diameter	−0.031	−0.026	−0.055	0.485	0.529	0.118
Tree height	HWD	0.046	0.359	−0.257	0.526	0.601	0.127
Tree height	Heart wood	0.334	0.638**	−0.394*	0.216	0.309	0.075
Tree diameter	HWD	0.896**	0.860**	0.841**	0.993**	0.964**	0.906**
Tree diameter	Heart wood	−0.281	0.484	0.090	−0.385	0.092	0.163
HWD	Heart wood	0.159	0.861**	0.611**	−0.281	0.348	0.561**

* and ** indicate significance at 5% and 1% level respectively. Values in parentheses indicate number of locations. HWD: Heart wood diameter (cm) pH: Soil reaction EC: Electrical conductivity. Critical correlation values with 6 degrees of freedom at 5% level = 0.707 and 1% level = 0.834. Critical correlation values with 8 degrees of freedom at 5% level = 0.632 and 1% level = 0.765. Critical correlation values with 11 degrees of freedom at 5% level = 0.553 and 1% level = 0.684. Critical correlation values with 13 degrees of freedom at 5% level = 0.514 and 1% level = 0.641. Critical correlation values with 25 degrees of freedom at 5% level = 0.381 and 1% level = 0.487. Critical correlation values with 71 degrees of freedom at 5% level = 0.232 and 1% level = 0.302.

3.3. Principal Component Model to Assess the Variability of Soil Parameters

Principal Component Analysis (PCA) was conducted on soil parameter data to assess variability and identify key components explaining this variation within each agro-climatic zone (ACZ). The PCA model was applied separately to ACZ-3 (15 locations), ACZ-4 (13 locations), ACZ-5 (27 locations), ACZ-6 (8 locations), and a pooled dataset comprising ACZ-2, ACZ-7, ACZ-8, ACZ-9, and ACZ-10 (10 observations). Additionally, PCA was performed on the combined data from all 73 locations across the different ACZs.

The eigenvalues and the percentage of variance explained by the principal components (PCs) for each ACZ are summarized in Table 5. The analysis identified five significant PCs for ACZ-5, while four significant PCs were observed in ACZ-4, ACZ-6, the pooled data of ACZ-2, 7, 8, 9, 10, and the overall pooled dataset of all 73 locations. In contrast, only three PCs were found to be significant in ACZ-3. The eigenvalues of the significant PCs ranged from, ACZ-3: 6.376 to 1.524, ACZ-4: 4.188 to 1.566, ACZ-5: 3.325 to 1.081, ACZ-6: 4.415 to 1.206, Pooled ACZ-2, 7, 8, 9, 10: 4.820 to 1.265, Pooled data (all 73 locations): 3.785 to 1.318.

In terms of total variance explained by the significant PCs, the highest cumulative variance (85.87%) was observed in the pooled data from ACZ-2, 7, 8, 9, and 10, Followed by ACZ-6 (84.87%), ACZ-4 (79.09%), ACZ-5 (77.07%), ACZ-3 (74.01%), and the lowest in the fully pooled dataset (64.72%).

The first principal component (PC1) accounted for the largest share of variance in each case: ACZ-3 had the highest at 49.05%, Followed by pooled ACZ-2, 7, 8, 9, 10 (37.08%), ACZ-6 (33.96%), ACZ-4 (32.21%), Pooled data from all 73 locations (29.12%) and ACZ-5 (25.58%).

3.3.1. Loadings of Soil Parameters on Principal Components under Different ACZs

The loadings of 13 soil parameters on the principal components (PCs) calibrated for different agro-climatic zones (ACZs) are presented in Table 6. Loadings with absolute values greater than or equal to ±0.60 were considered to significantly influence the respective PCs.

Under ACZ-3; PC1 significantly influenced by pH (0.873), EC (0.632), OC (0.774), N (0.644), P (0.885), Ca (0.710), S (0.940), Fe (−0.671), and Cu (−0.769). PC2 influenced by N (−0.682) and Mn (0.667). PC3 influenced by Zn (0.712).

Under ACZ-4; PC1 significantly influenced by EC (0.622), OC (0.725), N (0.721), Mg (0.768), S (0.907), and Zn (0.824). PC2 significantly influenced by K (−0.662), Mn (0.651), and Cu (−0.702). PC3 significantly influenced by Ca (−0.762) and Fe (0.683). PC4 influenced by P (0.716).

Table 5. Eigen values and variance (V) explained by PCs of soil parameters under different ACZs.

Agro-Climatic Zone (ACZ)	ACZ-3	ACZ-4	ACZ-5	ACZ-6	ACZ-2, 7, 8, 9, 10	Pooled
Locations	15	13	27	8	10	73
PC1	6.376	4.188	3.325	4.415	4.82	3.785

Continued

PC2	1.721	2.444	2.366	2.828	3.607	1.778
PC3	1.524	2.083	2.091	2.584	1.471	1.533
PC4		1.566	1.196	1.206	1.265	1.318
PC5			1.081			
V (PC1)	49.05	32.21	25.58	33.96	37.08	29.12
V (PC2)	13.24	18.80	18.20	21.75	27.75	13.68
V (PC3)	11.73	16.03	16.09	19.88	11.32	11.79
V (PC4)		12.05	9.20	9.28	9.73	10.14
V (PC5)			8.31			
Total	74.01	79.09	77.37	84.87	85.87	64.72

Under ACZ-5; PC1 significantly influenced by Ca (0.829), Mg (0.894), and S (0.855). PC2 significantly influenced by OC (0.878) and N (0.909). PC3 significantly influenced by EC (0.825), P (0.715), Fe (0.600), and Mn (0.678). PC4 influenced by pH (0.607) and Fe (−0.606). PC5 influenced by Zn (0.777).

Under ACZ-6; PC1 significantly influenced by pH (0.658), OC (0.881), N (0.881), P (0.683), Ca (−0.619), and Fe (−0.770). PC2 significantly influenced by EC (0.747) and Mg (0.831). PC3 significantly influenced by K (0.694) and Zn (−0.846). PC4 influenced by Mn (0.744).

Pooled Data from ACZ-2, 7, 8, 9, 10; PC1 significantly influenced by pH (0.828), EC (0.842), P (0.762), K (0.614), Ca (0.843), S (0.768), and Cu (0.837). PC2 significantly influenced by OC (0.876), N (0.876), Mg (−0.675), Mn (0.789), and Zn (−0.628). PC3 influenced by Fe (0.711).

Pooled Data from All 73 Locations; PC1 significantly influenced by pH (0.726), EC (0.620), Ca (0.641), and S (0.872). PC2 significantly influenced by OC (−0.728) and N (−0.782). PC3 significantly influenced by P (0.610) and Mn (0.670). PC4 influenced by K (0.658).

These findings are consistent with those reported by Parama et al. (2018a), who developed a principal component model to assess soil fertility variability in a micro-watershed region of Karnataka. Their study similarly identified a subset of soil parameters that most effectively captured variability in soil fertility data.

Table 6. Loadings of soil parameters on principal components under different ACZs.

Parameter	ACZ-3					ACZ-4			
	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4
pH	0.873*	0.240	0.112			0.370	−0.596	0.052	0.456
EC	0.632*	0.452	−0.435			0.622*	−0.479	0.106	0.326
OC	0.774*	−0.473	0.022			0.725*	−0.025	0.544	−0.092
Nitrogen	0.644*	−0.682*	0.090			0.721*	−0.078	0.572	−0.108

Continued

Phosphorus	0.885*	−0.084	0.309			−0.214	0.234	0.162	0.716*
Potassium	−0.476	0.310	0.235			−0.026	−0.662*	−0.448	0.322
Calcium	0.710*	0.272	−0.414			0.333	0.295	−0.762*	−0.264
Magnesium	0.592	−0.182	−0.593			0.768*	0.428	−0.339	0.005
Sulphur	0.940*	−0.079	0.245			0.907*	0.099	0.124	0.087
Iron	−0.671*	0.015	0.133			−0.447	0.294	0.683*	−0.223
Manganese	0.353	0.667*	0.236			−0.294	0.651*	0.120	0.498
Zinc	0.535	0.095	0.712*			0.824*	0.279	−0.111	−0.177
Copper	−0.769*	−0.318	0.026			−0.287	−0.702*	0.122	−0.457
			ACZ-5				**ACZ-6**		
pH	0.466	0.434	0.062	0.607*	0.132	0.658*	0.552	0.181	−0.124
EC	0.198	−0.096	0.825*	0.216	−0.258	−0.443	0.747*	0.278	0.007
OC	0.191	0.878*	−0.052	−0.348	0.133	0.881*	−0.155	0.409	0.141
Nitrogen	0.152	0.909*	0.008	−0.344	−0.077	0.881*	−0.156	0.409	0.141
Phosphorus	0.182	0.072	0.715*	0.146	0.461	0.683*	0.527	−0.314	0.142
Potassium	−0.500	0.535	−0.028	0.299	0.026	0.094	−0.517	0.694*	0.316
Calcium	0.829*	−0.130	−0.051	−0.188	−0.288	−0.619*	0.524	0.335	0.145
Magnesium	0.894*	0.157	0.028	0.051	−0.154	0.099	0.831*	0.193	−0.117
Sulphur	0.855*	0.040	0.044	0.079	0.030	0.558	0.096	−0.520	−0.498
Iron	0.120	−0.306	0.600*	−0.606*	0.165	−0.770*	−0.296	0.334	−0.116
Manganese	−0.418	0.217	0.678*	0.057	−0.117	0.323	0.094	−0.510	0.744*
Zinc	0.292	−0.175	−0.208	−0.015	0.777*	−0.249	−0.355	−0.846*	0.048
Copper	−0.484	0.255	0.159	−0.123	0.084	−0.542	0.419	−0.226	0.424
			ACZ-2, 7, 8, 9, 10				**Pooled from 73 Locations**		
pH	0.828*	0.126	−0.395	0.266		0.726*	0.235	0.153	0.279
EC	0.842*	0.040	0.179	0.233		0.620*	0.416	0.192	0.128
OC	−0.284	0.876*	−0.121	0.025		0.589	−0.728*	0.218	0.157
Nitrogen	−0.284	0.876*	−0.121	0.025		0.518	−0.782*	0.259	0.175
Phosphorus	0.762*	0.344	0.011	−0.266		0.425	0.279	0.610*	−0.129
Potassium	0.614*	−0.334	−0.361	0.553		−0.296	0.289	0.144	0.658*
Calcium	0.843*	0.136	0.368	0.125		0.641*	0.364	−0.112	0.047
Magnesium	0.298	−0.675*	0.471	−0.042		0.567	0.211	−0.238	−0.154
Sulphur	0.768*	0.380	0.392	−0.013		0.872*	0.084	0.027	−0.034
Iron	−0.380	0.408	0.711*	0.414		−0.390	0.071	0.472	−0.376
Manganese	0.244	0.789*	0.127	−0.382		−0.103	0.110	0.670*	−0.420
Zinc	0.117	−0.628*	0.163	−0.540		0.433	0.122	−0.340	−0.239
Copper	0.837*	0.158	−0.253	−0.368		−0.382	0.174	0.328	0.563

* indicates significant loading of either more than + 0.60 or less than − 0.60; pH: Soil reaction EC: Electrical conductivity (dS m^{-1}) OC: Organic carbon (%).

3.3.2. Grouping of Soil Parameters Based on Their Variability and Loadings on PCs

Soil parameters were evaluated based on their coefficient of variation (CV) and their loadings on the first principal component (PC1) across different agro-climatic zones (ACZs), specifically ACZ-3, ACZ-4, ACZ-5, ACZ-6, and the pooled dataset of ACZ-2, 7, 8, 9, and 10. Based on this comparison, soil parameters were classified into four quadrants (Q1 to Q4): Q1: Negative PC loadings with low CV, Q2: Positive PC loadings with low CV, Q3: Negative PC loadings with high CV, Q4: Positive PC loadings with high CV. This classification is illustrated in Figure 2, which compares the CV and PC1 loadings of soil parameters across the zones.

A comparison of CV and loadings of soil parameters on PC1 under ACZ-3, ACZ-4, ACZ-5 and ACZ-6 is given in Figure 2. Under ACZ-3, Cu occurred in Q1; while pH, EC and Mg occurred in Q2; K and Fe occurred in Q3; and OC, N, P, Ca, S, Zn and Mn occurred in Q4. Under ACZ-4, K occurred in Q1; while pH, EC, Ca and Mg occurred in Q2; P, Cu, Mn and Fe occurred in Q3; and OC, N, Zn and S occurred in Q4. Under ACZ-5, K, Cu and Mn occurred in Q1; while pH, EC, OC, N, P, Mg, Ca and Fe occurred in Q2; and S and Zn occurred in Q4. Under ACZ-6, pH, OC, N and K occurred in Q2; while EC, Ca, Fe, Cu & Zn occurred in Q3; and P, S, Mn & Mg occurred in Q4.

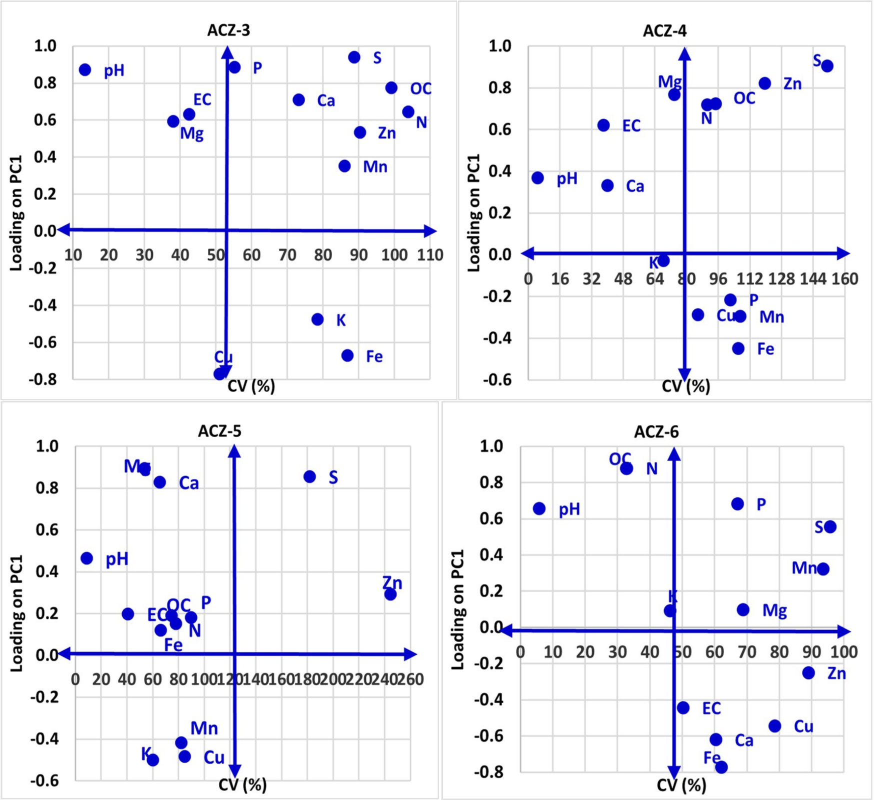


Figure 2. Assessment of soil parameters based on their variability and loadings on PC1 under ACZ-3, ACZ-4, ACZ-5 and ACZ-6.

A comparison of CV and loadings of soil parameters on PC2 under ACZ-3, ACZ-4, ACZ-5 and ACZ-6 is given in Figure 3. Under ACZ-3, Mg and Cu occurred in Q1; while pH and EC occurred in Q2; OC, N, P and S occurred in Q3; and K, Fe, Zn, Ca and Mn occurred in Q4. Under ACZ-4, pH, EC and K occurred in Q1; while Ca and Mg occurred in Q2; OC, N and Cu occurred in Q3; and P, S, Fe, Zn and Mn occurred in Q4. Under ACZ-5, EC, Ca and Fe occurred in Q1; while pH, OC, N, P, K, Mg, Mn and Cu occurred in Q2; Zn occurred in Q3; and S occurred in Q4. Under ACZ-6, OC, N and K occurred in Q1; while pH and EC occurred in Q2; Fe and Zn occurred in Q3; and P, Ca, Mg, Cu, S and Mn occurred in Q4.

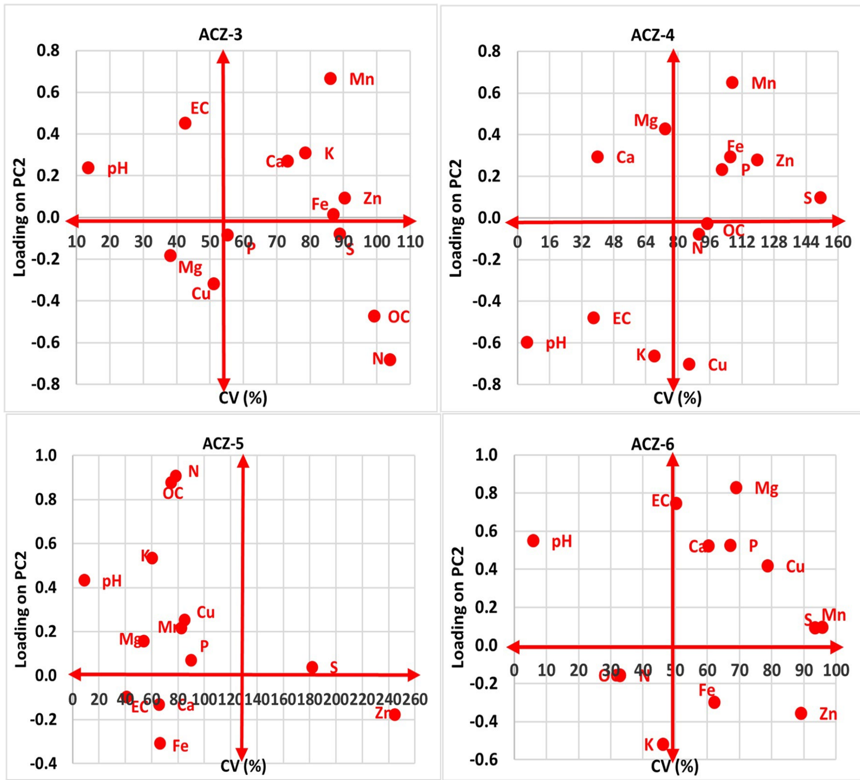


Figure 3. Assessment of soil parameters based on their variability and loadings on PC2 under ACZ-3, ACZ-4, ACZ-5 and ACZ-6.

A comparison of CV and loadings of soil parameters on PC3 under ACZ-3, ACZ-4, ACZ-5 and ACZ-6 is given in Figure 4. Under ACZ-3, EC and Mg occurred in Q1; while pH and Cu occurred in Q2; Ca occurred in Q3; and OC, N, P, K, Fe, S, Mn and Zn occurred in Q4. Under ACZ-4, K, Ca and Mg occurred in Q1; while pH and EC occurred in Q2; Zn occurred in Q3; and OC, N, P, Fe, Cu, Mn and S occurred in Q4. Under ACZ-5, OC, K and Ca occurred in Q1; while pH, EC, N, P, Mg, Cu, Fe and Mn occurred in Q2; Zn occurred in Q3; and S occurred in Q4. Under ACZ-6, pH, OC, N and K occurred in Q2; while P, Cu, Mn, S and Zn occurred in Q3; and EC, Ca, Fe and Mg occurred in Q4.

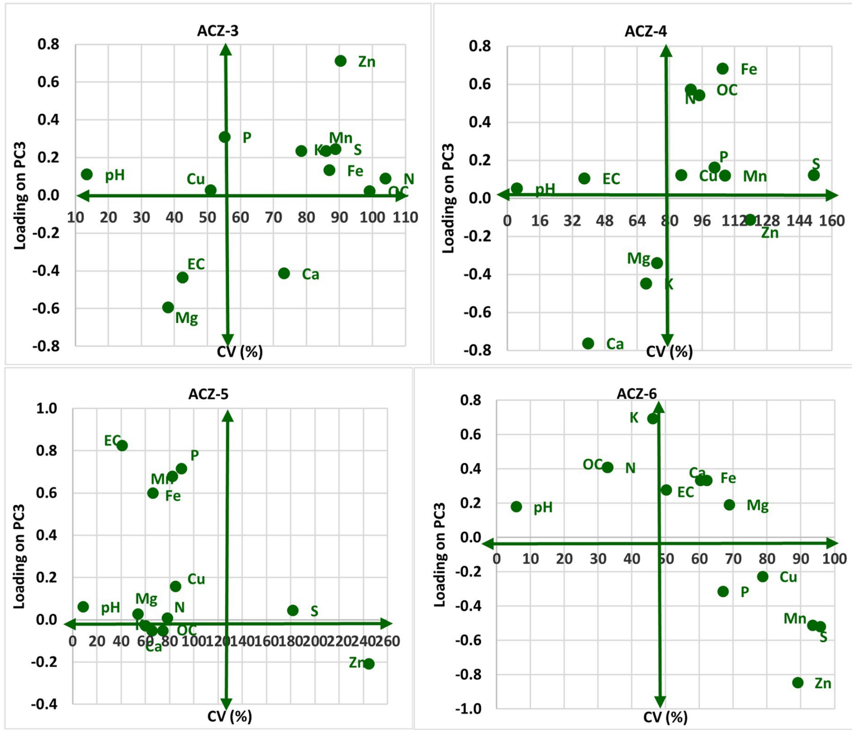
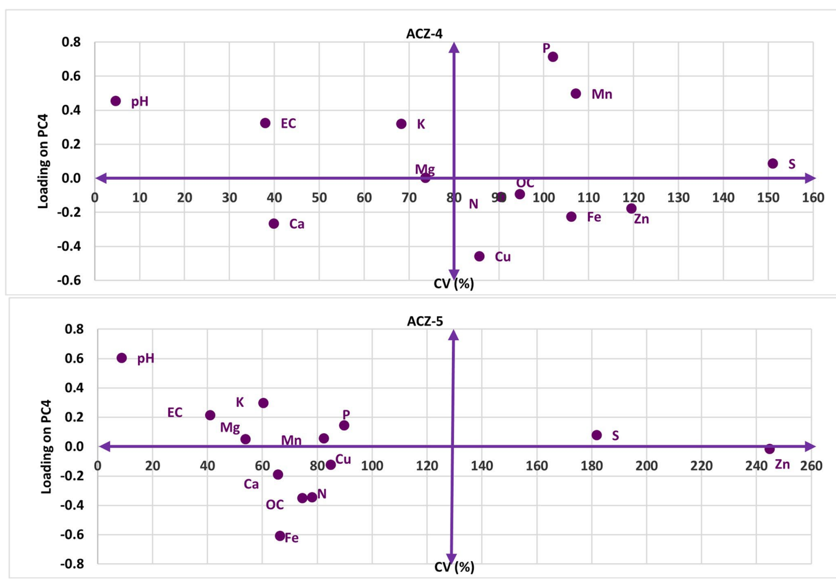


Figure 4. Assessment of soil parameters based on their variability and loadings on PC3 under ACZ-3, ACZ-4, ACZ-5 and ACZ-6.

A comparison of CV and loadings of soil parameters on PC4 under ACZ-4, ACZ-5 and ACZ-6 is given in Figure 5. Under ACZ-4, Ca occurred in Q1; while pH, EC, K and Mg occurred in Q2; OC, N, Cu, Fe and Zn occurred in Q3; and P, Mn and S occurred in Q4. Under ACZ-5, OC, N, Fe, Ca and Cu occurred in Q1; while pH, EC, P, K, Mg and Mn occurred in Q2; Zn occurred in Q3; and S occurred in Q4. Under ACZ-6, pH occurred in Q1; while EC, OC, N and K occurred in Q2; Fe, Mg and S occurred in Q3; and P, Ca, Cu, Zn and Mn occurred in Q4.



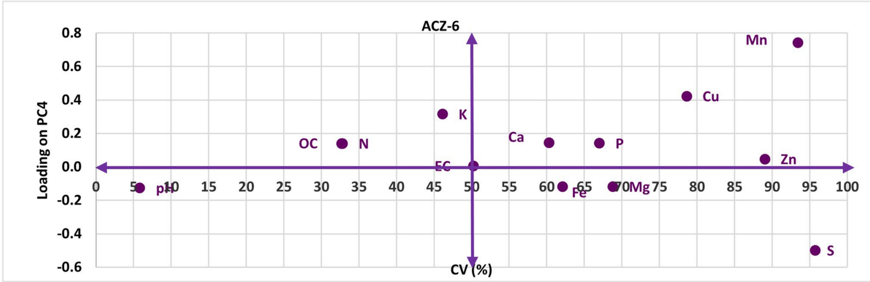


Figure 5. Assessment of soil parameters based on their variability and loadings on PC4 under ACZ-4, ACZ-5 and ACZ-6.

A comparison of the coefficient of variation (CV) and PC5 loadings for soil parameters under ACZ-5, as illustrated in **Figure 6**, revealed the following quadrant placements.

Quadrant 1 (Q1): Parameters (EC, N, Mg, Mn, and Ca) with negative loadings and low variability, Quadrant 2 (Q2): Parameters (pH, OC, P, K, Fe, and Cu) with positive loadings and low variability, Quadrant 4 (Q4): Parameters (S and Zn) with positive loadings and high variability. These results highlight that most soil parameters on PC5 under ACZ-5 are stable (low CV) and exert either positive or negative influence, with Q2 housing the largest number of positively influential and stable parameters.

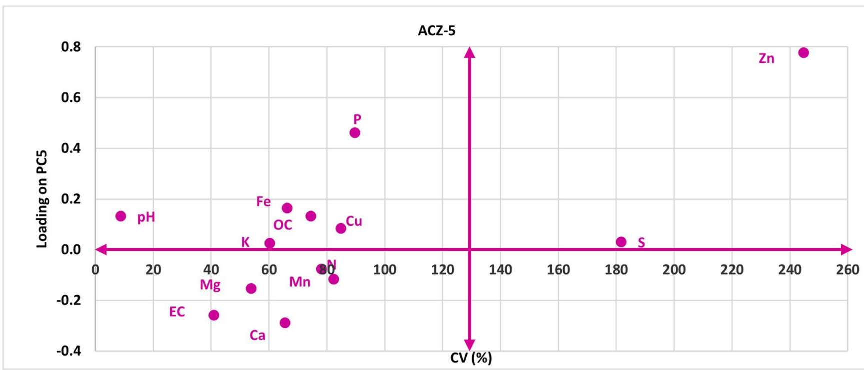


Figure 6. Assessment of soil parameters based on their variability and loadings on PC5 under ACZ-5.

Comparison of the coefficient of variation (CV) and principal component (PC) loadings of soil parameters on PC1 to PC4 using data pooled from ACZ-2, 7, 8, 9, and 10 are presented in **Figure 7**. The soil parameters were classified into quadrants based on their variability and loading values. Q2 parameters, especially under PC1 and PC2, represent key soil properties (e.g., pH, Ca, Mg, Mn, K) that are stable (low CV) and positively influential. Parameters in Q4 (e.g., EC, P, Zn, S, Cu, Fe) show high variability but also contribute strongly and positively to the variability captured by the principal components. However, Q3 parameters generally show high variability with negative loadings, indicating unstable or less favourable influence in the current context.

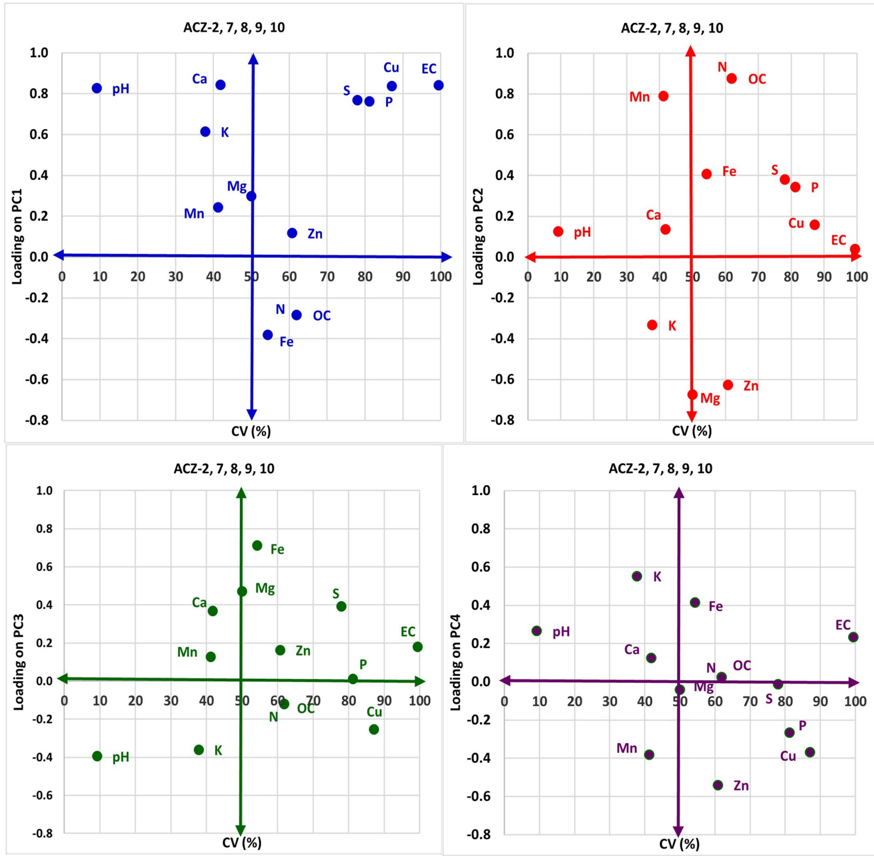


Figure 7. Assessment of soil parameters based on their variability and loadings on PC1, PC2, PC3 and PC4 when pooled over ACZ-2, 7, 8, 9, 10 zones.

The distribution of soil parameters into different quadrants determined by their coefficient of variation (CV) and loadings on various principal components (PCs) was analyzed across ACZ-3, ACZ-4, ACZ-5, ACZ-6, and pooled zones comprising ACZ-2, 7, 8, 9, and 10, as presented in Table 7. Based on PC1 Loadings: Majority of soil parameters were found in Quadrant 2 (Q2), indicating positive loadings with low variability. This was followed in order by Q4, Q3, and Q1. While based on PC2 Loadings: Most parameters occurred in Q4, followed by Q2, Q1, and Q3. In same line based on PC3 Loadings: Similar to PC2, the majority of parameters were concentrated in Q4, followed by Q2, Q3, and Q1. In PC4 Loadings: Most parameters appeared in Q2, followed by Q3, Q4, and Q1. However, PC5 Loadings (analyzed only for ACZ-5): The majority of soil parameters were found in Q2, followed by Q1 and Q4. These patterns suggest that many key soil parameters not only show positive and stable contributions to principal components but also exhibit low variability, especially under PC1 and PC4. These findings are consistent with those reported by Maruthi Sankar et al. (2014a), who observed a similar distribution of soil, fertilizer, and weather parameters into quadrants when analyzing variability using a principal component model in semi-arid Vertisol regions.

Table 7. Occurrence of soil parameters in different quadrangles based on their variability and loadings on different PCs.

Group (CV—Loading)	ACZ-3	ACZ-4	ACZ-5	ACZ-6	Pooled ACZ-2, 7, 8, 9, 10	Total
			PC1 vs CV			
Low - Low	Cu	K	K, Cu, Mn			5
Low - High	pH, EC, Mg	pH, EC, Ca, Mg	pH, EC, OC, N, P, Mg, Ca, Fe	pH, OC, N, K	pH, K, Ca, Mn, Mg	24
High - Low	K, Fe	P, Cu, Mn, Fe		EC, Ca, Fe, Cu, Zn	OC, N, Fe	14
High - High	OC, N, P, Ca, S, Zn, Mn	OC, N, Zn, S	S, Zn	P, S, Mn, Mg	EC, P, Zn, S, Cu	22
			PC2 vs CV			
Low - Low	Mg, Cu	pH, EC, K	EC, Ca, Fe	OC, N, K	K	12
Low - High	pH, EC	Ca, Mg	pH, OC, N, P, K, Mg, Mn, Cu	pH, EC	pH, Ca, Mn	17
High - Low	OC, N, P, S	OC, N, Cu	Zn	Fe, Zn	Mg, Zn	12
High - High	K, Fe, Zn, Ca, Mn	P, S, Fe, Zn, Mn	S	P, Ca, Mg, Cu, S, Mn	EC, OC, N, P, Fe, S, Cu	24
			PC3 vs CV			
Low - Low	EC, Mg	K, Ca, Mg	OC, K, Ca		pH, K	10
Low - High	pH, Cu	pH, EC	pH, EC, N, P, Mg, Cu, Fe, Mn	pH, OC, N, K	Mn, Ca	18
High - Low	Ca	Zn	Zn	P, Cu, Mn, S, Zn	OC, N, Cu	11
High - High	OC, N, P, K, Fe, S, Mn, Zn	OC, N, P, Fe, Cu, Mn, S	S	EC, Ca, Fe, Mg	EC, P, Zn, S, Mg, Fe	26
			PC4 vs CV			
Low - Low		Ca	OC, N, Fe, Ca, Cu	pH	Mn	8
Low - High		pH, EC, K, Mg	pH, EC, P, K, Mg, Mn	EC, OC, N, K	pH, K, Ca	17
High - Low		OC, N, Cu, Fe, Zn	Zn	Fe, Mg, S	P, Zn, Cu, Mg, S	14
High - High		P, Mn, S	S	P, Ca, Cu, Zn, Mn	EC, OC, N, Fe	13
			PC5 vs CV			
Low - Low			EC, N, Mg, Mn, Ca			5
Low - High			pH, OC, P, K, Fe, Cu			6
High - Low						
High - High			S, Zn			2

3.4. Loadings of Tree Parameters on Principal Components under Different Agro-Climatic Zones

The Principal Component Analysis (PCA) of tree growth and heartwood-related attributes revealed considerable variation among agro-climatic zones (ACZs), indicating that different growth parameters contribute differently to sandalwood productivity and heartwood formation under varying environmental conditions (Table 8). Parameters with loadings greater than +0.60 or less than −0.60 were considered significant contributors to the principal components.

In ACZ-3, tree diameter (−0.871) and heartwood diameter (−0.790) exhibited strong loadings on PC1, suggesting that stem girth and heartwood development were the primary sources of variability in this zone. Tree height (0.750) and heartwood content (0.669) were significantly associated with PC2, indicating that vertical growth and heartwood accumulation represented another important dimension of variation. Heartwood content also showed a significant negative loading on PC3 (−0.605), further emphasizing its importance in explaining growth variability. These findings suggest that in the Northern Dry Zone, diameter growth and heartwood development are the dominant factors influencing sandalwood performance.

Table 8. Loadings of tree parameters on significant principal components under different Agro-Climatic Zones.

Parameters	Agro-Climatic Zone-3			Agro-Climatic Zone-4		
	PC1	PC2	PC3	PC1	PC2	PC3
Age	−0.591	−0.166	−0.665*	0.832*	0.054	
TH	0.289	0.750*	0.082	0.361	0.894*	
TD	−0.871*	0.269	0.399	0.803*	−0.399	
HWD	−0.790*	0.543	0.131	0.977*	0.000	
HW	0.247	0.669*	−0.605*	0.883*	0.396	
	Agro-Climatic Zone-5			Agro-Climatic Zone-6		
Age	0.571	0.622*	0.294	0.659*	0.550	−0.371
TH	−0.287	0.434	0.790*	0.811*	0.319	−0.378
TD	0.585	−0.600*	0.514	0.887*	−0.347	0.295
HWD	0.906*	−0.374	0.178	0.906*	−0.256	0.313
HW	0.799*	0.153	−0.431	−0.095	0.949*	0.038
	Agro-Climatic Zone-2,7,8,9,10			Pooled over all ACZs		
Age	0.883*	−0.359	−0.254	0.699*	0.250	
TH	0.840*	−0.462	0.138	0.264	0.535	
TD	0.790*	0.378	0.471	0.809*	−0.394	
HWD	0.899*	0.344	0.236	0.951*	−0.160	
HW	0.559	0.031	−0.807*	0.645*	0.393	

* indicates a significant loading which is either more than + 0.60 or less than – 0.60.

In ACZ-4, age of trees (0.832), tree diameter (0.803), heartwood diameter (0.977), and heartwood content (0.883) were strongly loaded on PC1. The exceptionally high loading of heartwood diameter indicates that heartwood development is the most influential characteristic in this zone. The simultaneous association of tree age, stem diameter, and heartwood content suggests that heartwood accumulation is largely dependent on tree maturity and radial growth. Tree height (0.894) was significantly loaded on PC2, indicating that height growth represents an independent source of variation. Therefore, both tree maturity and stem growth are critical determinants of heartwood production in the Central Dry Zone.

In ACZ-5, heartwood diameter (0.906) and heartwood content (0.799) were the major contributors to PC1, highlighting heartwood formation as the principal factor governing variability in this zone. Tree age (0.622) and tree diameter (−0.600) significantly influenced PC2, while tree height (0.790) was strongly associated with PC3. These results suggest that although heartwood characteristics dominate sandalwood performance in the Eastern Dry Zone, tree age and growth attributes also contribute substantially to overall variability. The prominence of heartwood-related traits indicates that this zone offers favourable conditions for heartwood development.

In ACZ-6, tree age (0.659), tree height (0.811), tree diameter (0.887), and heartwood diameter (0.906) were significantly loaded on PC1, demonstrating that both growth and heartwood parameters jointly contribute to variability. Heartwood content (0.943) exhibited a very high loading on PC2, indicating that variation in heartwood accumulation is largely independent of other growth traits and constitutes a major component of sandalwood productivity in this zone. The results suggest that favourable growth conditions in the Southern Transition Zone support both vegetative growth and heartwood formation.

When data from ACZ-2, 7, 8, 9, and 10 were pooled, tree age (0.883), tree height (0.840), tree diameter (0.790), and heartwood diameter (0.899) showed strong positive loadings on PC1. This indicates that tree maturity and overall growth performance are the major determinants of variability across these agro-climatic regions. Heartwood content (−0.807) was significantly loaded on PC3, suggesting that heartwood accumulation represents a distinct source of variation independent of tree growth characteristics.

For the pooled dataset comprising all 73 locations, tree age (0.699), tree diameter (0.809), heartwood diameter (0.951), and heartwood content (0.645) were significantly associated with PC1. The highest loading observed for heartwood diameter (0.951) indicates that it is the single most important variable explaining overall variability across agro-climatic zones. The simultaneous contribution of tree age, stem diameter, and heartwood content confirms that heartwood production is closely linked to tree maturity and radial growth. These findings demonstrate that enhancing tree growth, particularly diameter increment, and extending rotation age are essential strategies for maximizing heartwood yield in sandalwood plantations.

Overall, the PCA results clearly indicate that tree age, tree diameter, heartwood diameter, and heartwood content are the most influential biological parameters governing sandalwood productivity across Karnataka. The consistent appearance of these variables among the leading principal components suggests that management practices aimed at promoting vigorous stem growth and facilitating heartwood development will have the greatest impact on improving sandalwood yield and economic returns. Furthermore, the high loadings of heartwood diameter and heartwood content across most ACZs underscore their value as reliable indicators for assessing plantation performance and determining optimal harvest timing.

4. Discussion

4.1. Discussion: Relationship between Rainfall, Temperature and Tree Parameters under Different Agro-Climatic Zones

The present study demonstrated that the influence of climatic variables on sandalwood growth and heartwood formation varied considerably across agro-climatic zones, highlighting the complex interaction between environmental conditions and physiological processes governing heartwood development. A particularly strong negative relationship between rainfall and temperature observed in ACZ-3 ($r = -0.966$) indicates the inherent climatic gradient within the zone, where increased precipitation was associated with lower ambient temperatures. Similar inverse relationships between rainfall and temperature have been reported in dry tropical environments where rainfall events moderate atmospheric temperatures and reduce evaporative demand (Kramer & Boyer, 1995).

One of the most important findings of the study was the positive association between rainfall and heartwood percentage in ACZ-5 ($r = 0.396$) and in the pooled ACZs 2, 7, 8, 9 and 10 ($r = 0.667$). This suggests that adequate moisture availability may promote physiological processes associated with heartwood formation. Heartwood development involves the transformation of sapwood tissues through deposition of extractives and aromatic compounds, processes that require sustained metabolic activity and carbohydrate availability (Taylor et al., 2002). Improved soil moisture resulting from adequate rainfall may enhance photosynthetic productivity and assimilate translocation, thereby supporting greater heartwood accumulation. Previous studies on sandalwood have similarly reported that moderate moisture availability favours growth and subsequent heartwood development (Nagaveni & Vijayalakshmi, 2003).

Conversely, temperature exhibited a significant negative association with heartwood traits in several zones. The negative relationship between temperature and heartwood yield in ACZ-5 ($r = -0.483$), heartwood diameter in ACZ-6 ($r = -0.730$), and pooled data ($r = -0.235$ to -0.283) suggests that elevated temperatures may adversely affect heartwood formation. High temperatures increase evapotranspiration demand, reduce soil moisture availability, and may induce physiological stress, ultimately restricting carbon allocation to secondary metabolites and heartwood tissues (Larcher, 2003). In sandalwood, heartwood formation is closely linked to the production of sesquiterpenes and aromatic compounds, processes that can be affected by environmental stress and reduced assimilate availability (Celedon & Bohlmann, 2018).

Interestingly, rainfall exhibited a significant negative relationship with tree height in the pooled dataset (r = −0.297). Although greater moisture availability generally promotes growth, this result may reflect the confounding influence of agro-climatic variability across Karnataka. Locations receiving higher rainfall are often characterized by lower solar radiation, increased cloud cover, and differing soil conditions, which may reduce height growth despite adequate moisture availability. Similar observations have been reported in tropical tree species where growth responses are determined by interactions among rainfall, temperature, soil fertility, and stand management rather than rainfall alone (Lambers et al., 2008).

The results collectively indicate that climatic variables influence sandalwood productivity through multiple pathways. While moderate rainfall appears beneficial for heartwood development, elevated temperatures tend to reduce heartwood formation and diameter growth. These findings support the view that heartwood production in sandalwood is governed by an optimal balance between moisture availability and thermal conditions. Therefore, agro-climatic zones characterized by moderate rainfall and relatively lower temperature regimes may provide favourable conditions for maximizing sandalwood heartwood production.

4.2. Relationships between Soil and Tree Parameters under Different Agro-Climatic Zones

The correlation analysis revealed strong and biologically meaningful relationships among soil fertility parameters, tree growth characteristics, and heartwood formation. The consistently high positive correlation between organic carbon and nitrogen across all agro-climatic zones confirms the fundamental role of soil organic matter as a major reservoir and source of plant-available nitrogen. This relationship is widely recognized in soil science because nitrogen mineralization is largely dependent on the decomposition of soil organic matter (Weil & Brady, 2017). The exceptionally high correlations observed in the present study (r = 0.906 - 0.991) indicate that soil organic carbon is a reliable indicator of overall soil fertility status in sandalwood plantations.

Tree diameter exhibited a strong positive relationship with heartwood percentage across most agro-climatic zones. This finding is consistent with the physiological process of heartwood formation, which generally increases as stem diameter expands and the proportion of older xylem tissues increases (Taylor et al., 2002). Larger trees possess greater conductive and storage tissues, facilitating the conversion of sapwood into heartwood. Similar relationships between stem diameter and heartwood yield have been reported in sandalwood and other valuable timber species (Arunkumar et al., 2011).

The significant association of heartwood percentage with tree age in ACZ-3, ACZ-5, and pooled datasets further confirms that heartwood formation is an age-dependent process. As trees mature, physiological ageing of xylem tissues promotes deposition of extractives and aromatic compounds characteristic of sandalwood heartwood. Earlier studies have consistently shown that both age and stem diameter are primary determinants of heartwood quantity and quality in Santalum album (Srimathi & Kulakarni 1980; Nagaveni & Vijayalakshmi, 2003).

Several important nutrient interactions were also observed. The strong positive associations among calcium, magnesium, and sulphur in ACZ-3, ACZ-4, and ACZ-5 suggest common geochemical origins and similar soil-forming processes influencing nutrient availability. Calcium and magnesium are major base cations involved in cell wall development, enzyme activation, and maintenance of soil structure, while sulphur plays an important role in protein synthesis and secondary metabolite production (Marschner, 2012). Their coordinated occurrence indicates balanced nutrient environments favourable for sandalwood growth.

The significant relationships between soil pH and nutrients such as calcium, phosphorus, magnesium, zinc, and sulphur demonstrate the central role of pH in regulating nutrient availability. Soil pH influences nutrient solubility, microbial activity, and root nutrient uptake efficiency (Weil & Brady, 2017). The positive correlation between pH and calcium observed across several zones suggests that calcium-rich soils maintain favourable pH conditions, enhancing nutrient availability and supporting tree growth. Conversely, the negative relationship between pH and iron indicates reduced iron solubility under higher pH conditions, a phenomenon widely documented in calcareous soils (Marschner, 2012).

The positive relationship between sulphur and organic carbon, nitrogen, zinc, copper, and iron highlights the integrated nature of soil nutrient cycling. Sulphur mineralization is often associated with organic matter decomposition, explaining its close association with carbon and nitrogen. Furthermore, sulphur contributes to the biosynthesis of amino acids and volatile compounds, which may indirectly influence sandalwood oil biosynthesis and heartwood quality (Celedon & Bohlmann, 2018).

The significant correlations between tree growth variables and soil nutrients indicate that nutrient availability influences growth performance and heartwood formation. Tree height showed positive associations with sulphur, nitrogen, zinc, and potassium in several zones, reflecting the importance of these nutrients in photosynthesis, protein synthesis, enzyme activation, and biomass accumulation. Potassium, in particular, regulates stomatal activity and water-use efficiency, making it especially important in the dry agro-climatic conditions prevalent across much of Karnataka (Marschner, 2012).

4.3. Principal Component Model to Assess the Variability of Soil Parameters

Principal Component Analysis (PCA) is a powerful multivariate statistical technique widely used to reduce data dimensionality and identify the most influential variables contributing to variability within complex datasets. In soil fertility studies, PCA helps distinguish key soil properties that govern nutrient dynamics and productivity by transforming correlated variables into a smaller set of independent principal components (PCs). In the present study, PCA was employed to evaluate the variability of thirteen soil parameters across different agro-climatic zones (ACZs) of Karnataka and to identify the dominant factors influencing soil fertility and, consequently, sandalwood growth.

The analysis revealed substantial differences in the soil fertility structure among agro-climatic zones. The number of significant principal components varied from three in ACZ-3 to five in ACZ-5, indicating that the complexity of soil nutrient interactions differed across climatic regions. The cumulative variance explained by the significant PCs ranged from 64.72 % in the pooled dataset of all 73 locations to 85.87% in the pooled dataset of ACZ-2, 7, 8, 9, and 10. Such high percentages of explained variance indicate that the selected PCs adequately represented the variability present in the original soil dataset. Similar observations have been reported by Parama et al. (2018a), who demonstrated that a limited number of PCs could effectively capture the majority of soil fertility variability in watershed ecosystems of Karnataka.

Among all zones, PC1 consistently explained the highest proportion of variation, ranging from 25.58% in ACZ-5 to 49.05% in ACZ-3. The dominance of PC1 suggests the existence of a common fertility gradient driven by a few major soil attributes. The exceptionally high contribution of PC1 in ACZ-3 indicates that soil fertility variation in this zone is largely governed by a single set of interrelated soil properties, whereas the lower contribution observed in ACZ-5 reflects a more complex nutrient environment requiring multiple PCs to explain variability. Similar patterns have been reported in soil quality assessments where heterogeneous environments generally require more components to capture nutrient interactions (Shukla et al., 2006).

The loadings of soil parameters on the principal components provide valuable insights into the nutrient factors governing soil fertility. In ACZ-3, PC1 was strongly associated with pH, electrical conductivity (EC), organic carbon (OC), nitrogen (N), phosphorus (P), calcium (Ca), sulphur (S), iron (Fe), and copper (Cu). The strong positive loadings of OC, N, P, Ca, and S indicate that these nutrients collectively form the primary fertility axis in this zone. Organic carbon and nitrogen are fundamental indicators of soil fertility because they regulate nutrient mineralization and microbial activity. The high loading of phosphorus further highlights its importance in sandalwood-growing soils, as phosphorus availability directly affects root development and nutrient uptake. Negative loadings of Fe and Cu suggest contrasting nutrient dynamics, possibly associated with soil pH and redox conditions.

In ACZ-4, PC1 was dominated by EC, OC, N, Mg, S, and Zn. This pattern indicates that both macro- and micronutrients play important roles in determining soil fertility. The strong association of magnesium and zinc suggests that these nutrients may be limiting factors influencing plant growth in this zone. Zinc deficiency is common in tropical soils and often affects enzyme activation and growth processes. The significant contribution of sulphur also highlights its role in protein synthesis and metabolic activity. These findings suggest that balanced nutrient management involving both macro- and micronutrients is essential for sustaining productivity in ACZ-4.

The PCA results for ACZ-5 revealed a distinct fertility pattern. PC1 was primarily influenced by calcium, magnesium, and sulphur, indicating that secondary nutrients constitute the major source of variability in this zone. PC2 was strongly associated with organic carbon and nitrogen, while PC3 was dominated by EC, phosphorus, iron, and manganese. The separation of nutrient groups into different principal components suggests that nutrient availability is governed by multiple independent processes. Such separation may result from variations in parent material, management practices, and climatic influences. The appearance of zinc as a separate component (PC5) further emphasizes the importance of micronutrient management in this region.

Under ACZ-6, PC1 was influenced by pH, organic carbon, nitrogen, phosphorus, calcium, and iron. The strong positive association between OC, N, and P demonstrates the close linkage between soil organic matter and nutrient availability. Organic matter acts as a reservoir of nutrients and improves soil structure, water retention, and microbial activity. The negative loading of iron suggests inverse relationships between available iron and other fertility indicators, which may be associated with pH-induced changes in micronutrient solubility. PC2 was characterized by EC and Mg, while PC3 highlighted the influence of potassium and zinc, indicating the importance of balanced nutrient supply in this agro-climatic zone.

The pooled dataset comprising ACZ-2, 7, 8, 9, and 10 exhibited the highest cumulative variance explained by PCA (85.87 %), demonstrating a well-defined fertility structure. PC1 was strongly associated with pH, EC, phosphorus, potassium, calcium, sulphur, and copper. This indicates that nutrient availability and soil chemical properties collectively govern fertility variation across these zones. PC2 was dominated by organic carbon, nitrogen, manganese, magnesium, and zinc, reflecting the importance of organic matter-mediated nutrient cycling. The emergence of iron as a distinct component in PC3 suggests independent variation in micronutrient availability.

When all 73 locations were pooled, the cumulative variance explained decreased to 64.72 %, indicating greater heterogeneity among zones. Nevertheless, PC1 remained strongly associated with pH, EC, calcium, and sulphur, highlighting these parameters as the most stable indicators of soil fertility across the sandalwood-growing regions. Organic carbon and nitrogen dominated PC2, while phosphorus and manganese influenced PC3, and potassium was associated with PC4. The persistence of these nutrients across different scales of analysis demonstrates their fundamental role in governing soil fertility and supporting sandalwood growth.

The quadrant analysis based on coefficient of variation (CV) and PC loadings provided further insights into the relative importance and stability of soil parameters. Parameters located in Quadrant 2 (positive loadings and low variability) are considered the most desirable because they contribute significantly to soil fertility while remaining relatively stable across locations. Across most ACZs, pH, EC, calcium, magnesium, organic carbon, and nitrogen frequently occurred in Q2, indicating their consistent and positive contribution to soil fertility. In contrast, parameters located in Quadrant 4 exhibited high variability despite positive loadings, suggesting that they contribute substantially to fertility differences among sites. Nutrients such as sulphur, phosphorus, zinc, manganese, and copper frequently appeared in this quadrant, indicating potential opportunities for site-specific nutrient management.

The predominance of soil parameters in Quadrants 2 and 4 across PCs demonstrates that both stable fertility indicators and highly variable nutrients influence soil productivity in sandalwood plantations. Similar observations were reported by Maruthi Sankar et al. (2014a), who found that nutrient parameters with high PC loadings and moderate variability served as effective indicators of soil productivity in semi-arid Vertisols. The present findings therefore suggest that management strategies should focus not only on maintaining stable soil properties such as pH, organic carbon, and calcium but also on correcting highly variable nutrients such as sulphur, zinc, manganese, and phosphorus that contribute significantly to spatial fertility variation.

Overall, the PCA results clearly demonstrate that soil fertility variability across Karnataka's agro-climatic zones is governed by a combination of soil reaction (pH), organic matter status, major nutrients (N, P, K), secondary nutrients (Ca, Mg, S), and micronutrients (Fe, Mn, Zn, Cu). The identification of these key fertility indicators provides a scientific basis for developing zone-specific nutrient management strategies aimed at enhancing sandalwood growth and heartwood development. The strong contribution of organic carbon, nitrogen, phosphorus, calcium, magnesium, and sulphur across multiple zones further emphasizes their critical role in sustaining soil productivity and supporting long-term plantation performance.

4.4. Loadings of Tree Parameters on Principal Components under Different Agro-Climatic Zones

The Principal Component Analysis (PCA) of tree growth and heartwood-related attributes revealed substantial variation among agro-climatic zones (ACZs), indicating that the relative importance of growth and heartwood traits differs according to environmental conditions. PCA is an effective multivariate technique for identifying the major biological attributes responsible for variability within populations and has been widely used in forestry to characterize growth patterns, wood quality traits, and yield determinants. In the present study, tree age, tree height, tree diameter, heartwood diameter, and heartwood content were evaluated to determine their contribution to sandalwood productivity and heartwood formation across different agro-climatic zones of Karnataka.

The PCA results demonstrated that heartwood-related traits, particularly heartwood diameter and heartwood content, consistently emerged as major contributors to variability across most ACZs. This finding is biologically significant because heartwood represents the economically valuable portion of sandalwood and is directly associated with oil accumulation and market value. Previous studies have reported that heartwood formation is strongly influenced by tree age, stem diameter, and environmental conditions, making these variables critical indicators of sandalwood productivity (Nagaveni & Vijayalakshmi, 2003).

4.4.1. ACZ-3: Dominance of Stem Diameter and Heartwood Development

In ACZ-3, tree diameter (−0.871) and heartwood diameter (−0.790) exhibited strong loadings on PC1, indicating that radial growth and heartwood formation were the principal sources of variability. The strong association between these two variables suggests that heartwood development is closely linked to stem girth expansion. As trees increase in diameter, the transition of sapwood to heartwood accelerates, resulting in larger heartwood cores. Tree height (0.750) and heartwood content (0.669) loaded significantly on PC2, indicating that vertical growth and heartwood accumulation constitute a second independent dimension of variation. Interestingly, heartwood content also showed a significant negative loading on PC3 (−0.605), highlighting its complex role in explaining growth variability. The occurrence of heartwood content across multiple PCs suggests that heartwood formation in ACZ-3 is influenced by several interacting biological processes rather than a single growth factor. Overall, the PCA results indicate that diameter growth and heartwood development are the dominant determinants of sandalwood performance in the Northern Dry Zone.

4.4.2. ACZ-4: Influence of Tree Maturity on Heartwood Formation

In ACZ-4, age (0.832), tree diameter (0.803), heartwood diameter (0.977), and heartwood content (0.883) were strongly associated with PC1. Among these variables, heartwood diameter exhibited the highest loading, indicating that it is the most influential trait governing variability within this zone. The simultaneous contribution of age, stem diameter, and heartwood content suggests that heartwood accumulation is strongly dependent on tree maturity and radial growth. Heartwood formation in sandalwood generally begins after a certain physiological age and increases progressively with tree growth. Therefore, the strong association between age and heartwood traits observed in ACZ-4 confirms earlier findings that mature trees possess greater heartwood volume and higher heartwood percentages (Brand & Pronk, 2011). Tree height was independently represented by PC2 (0.894), indicating that height growth contributes to variability but operates independently of heartwood development. These findings suggest that management practices aimed at enhancing stem growth and maintaining plantations for longer rotations could substantially improve heartwood yield in the Central Dry Zone.

4.4.3. ACZ-5: Heartwood Traits as Primary Determinants of Variability

The PCA results for ACZ-5 revealed a distinct pattern in which heartwood diameter (0.906) and heartwood content (0.799) dominated PC1. This indicates that heartwood formation is the principal factor explaining variability among sandalwood trees in the Eastern Dry Zone. The predominance of heartwood-related traits suggests that environmental conditions in this zone may favour the physiological processes associated with heartwood initiation and development. Tree age (0.622) and tree diameter (−0.600) significantly influenced PC2, while tree height (0.790) was strongly associated with PC3. The separation of these growth variables into different PCs indicates that age, radial growth, and height growth contribute independently to overall variability. Similar separation of growth and wood-quality traits has been observed in other forest tree species, where wood formation processes are influenced by physiological factors distinct from those controlling vegetative growth (Zobel & van Buijtenen, 1989). The strong representation of heartwood parameters across the principal components highlights the suitability of ACZ-5 for sandalwood production aimed at maximizing heartwood yield.

4.4.4. ACZ-6: Combined Influence of Growth and Heartwood Traits

In ACZ-6, age (0.659), tree height (0.811), tree diameter (0.887), and heartwood diameter (0.906) were significantly loaded on PC1. This indicates that both vegetative growth and heartwood formation jointly contribute to variability in the Southern Transition Zone. The simultaneous occurrence of all major growth parameters within the first principal component suggests a highly integrated growth system where favourable environmental conditions support both biomass accumulation and heartwood development. Heartwood content showed an exceptionally high loading on PC2 (0.949), indicating that variation in heartwood accumulation occurs independently of other growth characteristics. This finding suggests that while tree growth provides the structural framework for heartwood formation, additional physiological or environmental factors influence the extent of heartwood accumulation. Similar observations have been reported by Climent et al. (2002), who noted that heartwood formation is influenced not only by growth but also by site-specific environmental conditions and genetic factors. The results indicate that ACZ-6 provides favourable conditions for achieving both rapid growth and substantial heartwood production.

4.4.5. Pooled Analysis of ACZ-2, 7, 8, 9, and 10

When data from ACZ-2, 7, 8, 9, and 10 were pooled, tree age (0.883), tree height (0.840), tree diameter (0.790), and heartwood diameter (0.899) exhibited strong positive loadings on PC1. This indicates that tree maturity and overall growth performance are the major determinants of variability across these agro-climatic regions. The high loading of heartwood diameter further confirms the central role of heartwood formation in sandalwood productivity. Heartwood content (−0.807) was significantly associated with PC3, suggesting that heartwood accumulation constitutes a distinct source of variation independent of general growth characteristics. This separation implies that trees with similar growth performance may differ considerably in their ability to produce heartwood. Such variability may arise from genetic differences, micro-site conditions, or physiological processes governing heartwood formation. Therefore, heartwood content should be considered independently when selecting superior trees for breeding and plantation development.

4.4.6. Pooled Analysis across All Agro-Climatic Zones

For the pooled dataset comprising all 73 locations, age (0.699), tree diameter (0.809), heartwood diameter (0.951), and heartwood content (0.645) were strongly associated with PC1. The exceptionally high loading of heartwood diameter (0.951) indicates that it is the single most important variable explaining variability across Karnataka's sandalwood-growing regions. This finding reinforces the concept that heartwood diameter serves as an effective indicator of both heartwood quantity and economic value.

The simultaneous contribution of age, diameter, and heartwood content demonstrates that heartwood production is fundamentally linked to tree maturity and radial growth. Previous studies have consistently reported positive relationships between age, diameter growth, and heartwood yield in sandalwood (Nagaveni & Vijayalakshmi, 2003; Brand & Pronk, 2011). Consequently, management strategies that promote vigorous diameter growth and allow sufficient time for heartwood development are likely to maximize economic returns from sandalwood plantations.

4.5. Implications for Sandalwood Management and Improvement

The PCA results collectively demonstrate that tree age, tree diameter, heartwood diameter, and heartwood content are the most influential biological parameters governing sandalwood productivity across Karnataka. The recurring appearance of these variables among the principal components highlights their importance as key indicators of plantation performance.

Among all traits evaluated, heartwood diameter emerged as the most consistent and influential variable across agro-climatic zones. This finding is particularly important because heartwood diameter can serve as a reliable surrogate measure for estimating heartwood volume and economic value. Furthermore, the strong association between tree diameter and heartwood traits suggests that silvicultural practices aimed at enhancing radial growth, such as optimal spacing, nutrient management, and host management, can indirectly improve heartwood yield.

The results also indicate that extending rotation age may significantly increase heartwood accumulation, particularly in zones where age and heartwood traits are strongly associated. Therefore, site-specific management strategies should focus on maximizing stem growth during the early stages of plantation development while ensuring adequate maturity for heartwood formation before harvest.

Overall, the PCA clearly demonstrates that heartwood diameter and heartwood content are the most reliable indicators of sandalwood productivity, while tree age and diameter provide the biological foundation for heartwood development. These findings provide valuable guidance for breeding programmes, plantation management, and harvesting decisions aimed at improving heartwood yield and enhancing the economic sustainability of sandalwood cultivation.

5. Conclusions

Significant correlation existed between rainfall and heartwood under ACZ-5 (0.396) and when pooled over ACZ-2, 7, 8, 9, 10 (0.667). Significant negative correlation of temperature existed with (i) heartwood under ACZ-5 (−0.483); (ii) heartwood diameter under ACZ-6 (−0.730). Under ACZ-3, ACZ-4, ACZ-5, ACZ-6 and when pooled over ACZ-2, 7, 8, 9, 10, (i) OC had significant correlation with N; while (ii) heartwood had significant correlation with tree diameter. Similarly, (i) Ca had significant correlation with Mg (ACZ-3, ACZ-4, ACZ-5) and S (ACZ-3, ACZ-5, Pooled ACZs); while (ii) EC had significant correlation with Ca (ACZ-3, ACZ-6, Pooled ACZs) and pH (ACZ-3, ACZ-4, Pooled ACZs); (iii) tree height had with S (ACZ-3, ACZ-6, Pooled ACZs); and (iv) heartwood had with tree age (ACZ-3, ACZ-5, Pooled ACZs). EC had significant correlation with S (ACZ-4, Pooled ACZs); while (ii) heartwood had with tree height and HWD, and Mg had with S (ACZ-4, ACZ-5); (iii) S had with N, OC and Zn (ACZ-3, ACZ-4); (iv) P had with S, Cu and pH had with Ca and Cu (ACZ-3, Pooled ACZs), tree height (ACZ-3, ACZ-6) and Fe (ACZ-5, ACZ-6); (v) pH had with S (ACZ-3, ACZ-5) and Cu (ACZ-3, Pooled ACZs); (vi) tree height had with tree age (ACZ-6, Pooled ACZs); (vii) P had with Fe, and tree diameter had with pH (ACZ-5, ACZ-6). Relationships of (i) EC with P (ACZ-5) and tree height (Pooled ACZs); (ii) Fe with HWD (ACZ-5); (iii) Mg with Cu (ACZ-3) and Zn (ACZ-4); (iv) tree height with OC, N and Zn (ACZ-3); (v) K with tree height (ACZ-5); (vi) pH with Fe, P and Zn (ACZ-3), Mg (ACZ-5); (vii) S with Cu and Fe (ACZ-3); (viii) tree age with HWD (ACZ-4) and Fe (ACZ-6) were significant.

Based on principal component analysis, 5 PCs were significant under ACZ-5; compared to 4 under ACZ-4, ACZ-6, pooled data of ACZ-2, 7, 8, 9, 10, and pooled data of all ACZs; and 3 under ACZ-3. Maximum variance of 85.87% was explained by PCs under pooled data of ACZ-2, 7, 8, 9, 10, followed by 84.87% under ACZ-6, 79.09% under ACZ-4, 77.07% under ACZ-5, 74.01% under ACZ-3 and 64.72 % when data were pooled over 73 locations. Under ACZ-3, pH (0.873), EC (0.632), OC (0.774), N (0.644), P (0.885), Ca (0.710), S (0.940), Fe (−0.671) and Cu (−0.769) were significantly loaded on PC1; compared to N (−0.682) and Mn (0.667) on PC2; and Zn (0.712) on PC3. Under ACZ-4, EC (0.622), OC (0.725), N (0.721), Mg (0.768), S (0.907) and Zn (0.824) were significantly loaded on PC1; compared to K (−0.662), Mn (0.651) and Cu (−0.702) on PC2; Ca (−0.762) and Fe (0.683) on PC3; and P (0.716) on PC4. Under ACZ-5, Ca (0.829), Mg (0.894) and S (0.855) were significantly loaded on PC1; compared to OC (0.878) and N (0.909) on PC2; EC (0.825), P (0.715), Fe (0.600) and Mn (0.678) on PC3; pH (0.607) and Fe (−0.606) on PC4; and Zn (0.777) on PC5. Under ACZ-6, pH (0.658), OC (0.881), N (0.881), P (0.683), Ca (−0.619) and Fe (−0.770) were significantly loaded on PC1; compared to EC (0.747) and Mg (0.831) on PC2; K (0.694) and Zn (−0.846) on PC3; and Mn (0.744) on PC4. When data were pooled over ACZ-2, 7, 8, 9, 10, pH (0.828), EC (0.842), P (0.762), K (0.614), Ca (0.843), S (0.768) and Cu (0.837) were significantly loaded on PC1; compared to OC (0.876), N (0.876), Mg (−0.675), Mn (0.789) and Zn (−0.628) on PC2; and Fe (0.711) on PC3. When data were pooled over 73 locations, pH (0.726), EC (0.620), Ca (0.641) and S (0.872) were significantly loaded on PC1; compared to OC (−0.728) and N (−0.782) on PC2; P (0.610) and Mn (0.670) on PC3; and K (0.658) on PC4.

Based on CV (%) and loadings of parameters on PCs under different ACZs, parameters were grouped into 4 quadrangles viz., (i) Q1 representing negative loadings on PCs with low CV; (ii) Q2 representing positive loadings on PCs with low CV; (iii) Q3 representing negative loadings on PCs with high CV; and (iv) Q4 representing positive loadings on PCs with high CV. A comparison of CV and loadings on the leading PC1 indicated that under ACZ-3, Cu occurred in Q1; while pH, EC and Mg occurred in Q2; K and Fe occurred in Q3; and OC, N, P, Ca, S, Zn and Mn occurred in Q4. Under ACZ-4, K occurred in Q1; while pH, EC, Ca and Mg occurred in Q2; P, Cu, Mn and Fe occurred in Q3; and OC, N, Zn and S occurred in Q4. Under ACZ-5, K, Cu and Mn occurred in Q1; while pH, EC, OC, N, P, Mg, Ca and Fe occurred in Q2; and S and Zn occurred in Q4. Under ACZ-6, pH, OC, N and K occurred in Q2; while EC, Ca, Fe, Cu and Zn occurred in Q3; and P, S, Mn and Mg occurred in Q4. A comparison of CV and loadings on PC1 when data were pooled over ACZ-2, 7, 8, 9 and 10 indicated that pH, K, Ca, Mn and Mg occurred in Q2; while OC, N and Fe occurred in Q3; and EC, P, Zn, S and Cu occurred in Q4. Similar groupings of parameters were made when CV and loadings of parameters on PC2, PC3, PC4 and PC5 were considered. The study indicated that pH, EC and Mg under ACZ-3; pH, EC, Ca and Mg occurred under ACZ-4; pH, EC, OC, N, P, Mg, Ca and Fe under ACZ-5; pH, OC, N and K under ACZ-6; pH, K, Ca, Mn and Mg when pooled over ACZ-2, 7, 8, 9 and 10 had low CV and significant and positive loadings on the leading 1st PC calibrated for the data. The superior parameters identified based on the study would significantly influence the sandalwood tree growth parameters and are useful to attain maximum heartwood under different ACZs of Karnataka. The findings are also useful for attaining maximum heartwood and other tree growth parameters under similar soil and agro-climatic conditions.

6. Recommendations

1) Rainfall positively influenced heartwood formation, whereas higher temperatures negatively affected heartwood content and heartwood diameter, highlighting the importance of moisture availability for sandalwood productivity.

2) Organic carbon showed a strong positive association with nitrogen across all agro-climatic zones, indicating the importance of maintaining soil organic matter for sustained growth.

3) In all ACZs Heartwood development was consistently associated with tree diameter and tree age, suggesting that promoting stem growth and extending rotation age can enhance heartwood yield.

4) Significant interrelationships among calcium, magnesium, sulphur, pH, and EC demonstrate the critical role of balanced soil fertility in sandalwood growth and heartwood formation is seen all ACZs.

5) Principal Component Analysis (PCA) revealed that a few key soil properties explained most of the variability in sandalwood performance, with pH, EC, organic carbon, nitrogen, calcium, magnesium, sulphur, phosphorus, and potassium emerging as major determinants.

6) Parameters exhibiting low variability and high positive PCA loadings, particularly pH, EC, Ca, Mg, OC, and N were identified as the most reliable indicators for site-specific management.

7) The study demonstrates that integrating climate, soil fertility, and tree growth information provides an effective framework for identifying suitable cultivation sites and developing precision management strategies for sandalwood plantations.

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Author Contributions

B.N.D.—Planned and executed the work in field and drafted manuscript and finalised; G.R.M.S.—Helped in data compilation, analysis of data and drafting the manuscript; All authors have read and agreed to the published version of the manuscript.

Ethics Approval and Consent to Participate

The collection of growth data and soil samples from farmers field used in our study are in accordance with the local or national guidelines.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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