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Differentiating Heartwood and Sapwood in *Tectona grandis* Linn.f. (Teak) Using the Electric Resistance Tomograph (ERT)

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Abstract

This study investigates the effectiveness of Electric Resistance Tomograph (ERT) as a non-invasive, accurate, and cost-effective method compared to traditional destructive methods for distinguishing between heartwood and sapwood in *Tectona grandis* L.f. (teak), a species valued for its durable timber. ERT is a sophisticated diagnostic tool that produces high-resolution tomographic images by capturing differences in electrical resistivity, which are influenced by variations in moisture content and conductivity within the wood. Teak discs were analysed by placing sensors at uniform intervals around their circumference and connecting them to an ERT multi-cable system. The resulting tomograms were then compared with manually recorded sapwood-heartwood (SW-HW) boundaries. The ERT images displayed a distinct resistivity gradient, with lower resistivity values indicating sapwood (blue zones) and higher values corresponding to heartwood (red zones). A strong linear correlation ($R^2 = 0.93$) between ERT-derived and manually measured heartwood areas confirmed the method's accuracy. The study further discusses how environmental conditions may affect resistivity readings and suggests improvements for ERT calibration to enhance its field applicability. These findings demonstrate the potential of ERT as a reliable, non-destructive technique for assessing internal wood structure and quality in teak, with promising applications in forest management, timber grading, and tree breeding programs for other heartwood-producing species.

Keywords

Electric resistance tomograph; *Tectona grandis*; Heartwood; Sapwood; Non-destructive testing

1. Introduction

Tectona grandis L.f., commonly known as teak, a tropical hardwood species belonging to the family Lamiaceae (formerly Verbenaceae), is renowned for its high-quality timber. *T. grandis* includes varieties such as Burmese teak, Central Province (CP) teak, and Nagpur teak. The species is native to South and Southeast Asia, primarily found in India, Bangladesh, Myanmar, Thailand, Sri Lanka, Indonesia, and Malaysia [1]. Over time, teak has been naturalized and widely cultivated in tropical regions of Africa, such as Côte d'Ivoire, Nigeria, Sierra Leone, the United Republic of Tanzania, and Togo, as well as in Latin America and the Caribbean, including Costa Rica, Colombia, Ecuador, El Salvador, Panama, Trinidad and Tobago, and Venezuela. It is also grown on Pacific islands like Papua New Guinea, Fiji, and the Solomon Islands, and in northern Australia [1, 2]. Molecular studies indicate that teak has only two major genetic origins: one from India and the other from Myanmar and Laos [3].

T. grandis is among the world's most valuable timber species, with enduring global demand due to its exceptional wood properties. Its unique combination of mechanical strength, dimensional stability, and aesthetic appeal has made it a preferred choice for a wide range of applications. The high natural oil content contributes to its durability and resistance to decay, making it ideal for indoor and outdoor flooring, paneling, furniture, construction, and marine use, including boat building. Teak's low shrinkage, ease of machining, strength, and resistance to weathering and pests such as termites and fungi have sustained its popularity over centuries, especially in traditional boatbuilding and bridge construction in Asia. Its ability to take polish and finish well with minimal treatment further enhances its value in modern woodworking and furniture industries.

2. Need for Electric Resistance Tomograph (ERT)

The Electric Resistance Tomograph (ERT) is a modern, advanced technique increasingly used for non-invasive tree inspections. It is recognized for being fast, precise, and cost-effective in detecting internal decay and structural defects in living trees. In recent years, tomographic methods have gained prominence for their effectiveness in assessing internal decay [4, 5]. ERT, in particular, can identify early stages of wood rot often before they become detectable by acoustic tomography [5]. However, while tomography can accurately pinpoint emerging decay zones, subtle resistivity differences may sometimes be overlooked due to limitations in the color resolution of tomographic images [6].

In addition to decay detection, ERT also offers a minimally invasive and precise approach for differentiating between heartwood and sapwood [6]. For instance, Bieker and Rust [7] successfully used ERT to estimate the conductive area of sapwood in Scots pine (*Pinus sylvestris* L.), demonstrating its broader potential in tree physiology and wood quality assessments.

2.1 Basic Principle

The Electric Resistance Tomograph (ERT) instrument operates based on variations in wood moisture content to generate tomographic images. It produces a visual map of electrical resistivity distribution across a tree cross-section. These variations in resistivity are influenced primarily by moisture content, but also by wood cell structure and other internal properties. Typically, the sapwood rich in moisture exhibits low resistivity and is displayed in shades of blue, while the drier heartwood shows higher resistivity and appears in red. The sharp decline in moisture content from sapwood to heartwood enables clear demarcation between these two zones, allowing ERT to effectively estimate their respective widths.

In a healthy tree, the concentric ring structure and dense central wood offer high electrical resistance, which gradually decreases toward the outer bark. In contrast, in trees affected by decay, resistivity in the center often decreases due to increased water mobility and accumulation, as well as wood degradation processes that release ions [8]. These changes lead to distinct resistivity anomalies that correspond to the presence and extent of wood decay or cavities. Consequently, ERT proves useful for the early detection of structural defects in hardwood trees.

Moreover, since electrical resistance and its inverse, electrical conductivity, reflect the physical and structural characteristics of wood, ERT also provides insights into internal tree health. However, it is important to note that the data obtained is limited to the specific region where the multi-electrode sensors are applied. For a comprehensive evaluation, measurements must be taken at multiple heights along the tree trunk. ERT can generate 2D cross-sectional resistivity images at various stem heights, displaying a color gradient from blue (low resistance) to red (high resistance). By stacking or superimposing these 2D slices, a 3D model of the stem's internal structure can be constructed. This 3D visualization enhances the interpretation of sapwood, heartwood, decay zones, and stress distribution within the tree.

Therefore, the present study was undertaken to evaluate the accuracy and applicability of ERT in distinguishing sapwood and heartwood in a tropical hardwood species, with an emphasis on its potential for non-destructive tree assessment.

3. Materials and Methods

The study was conducted at the Institute of Wood Science and Technology, Bengaluru. A total of thirty-three distinct teak (*Tectona grandis*) discs were selected, labeled, and their circumferences recorded. Based on the circumference of each disc, 24 nails were uniformly inserted at equidistant points along the perimeter to ensure balanced electrode distribution and generate clear tomographic images. For smaller discs, only 12 nails were used.

To facilitate electrical conductivity, the discs were soaked in water for approximately 10-15 minutes, allowing sufficient moisture absorption. Once adequately moistened, excess water was removed, and the multi-cable electrodes from the ERT instrument were connected to the nails, as illustrated in Figure 1. This setup enabled the capture of resistivity-based tomographic images.

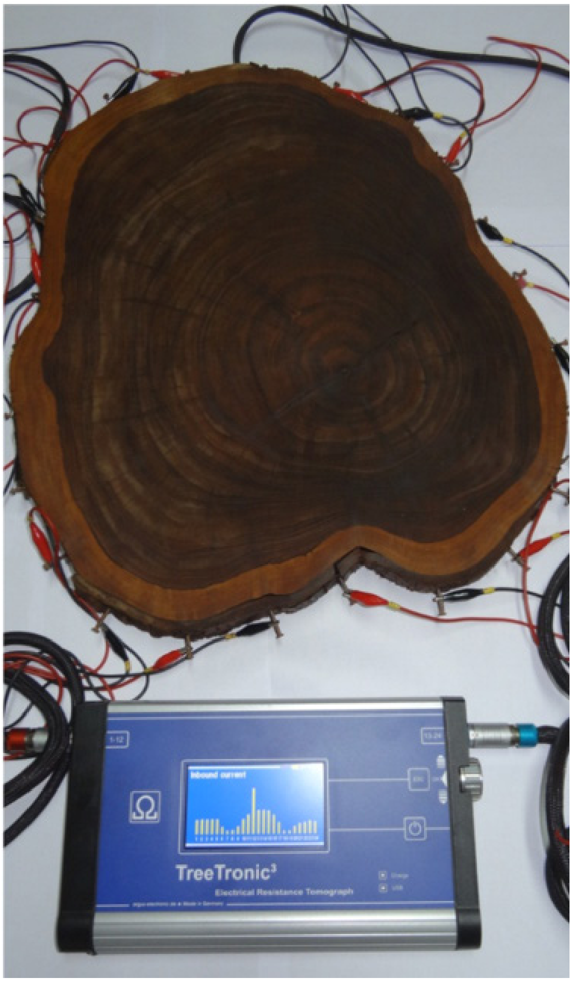


Figure 1. The **Electric Resistance Tomograph (ERT) is connected to a moist teak disc.**

The delineation of heartwood and sapwood boundaries was performed manually by visually identifying the colour contrast between the two zones. Two perpendicular measurements were taken for both the heartwood diameter and the total disc diameter (sapwood + heartwood), and the average of these values was used for further analysis.

Tomographic data obtained from ERT were processed using the PICUS TreeTronic software. Measurements of the heartwood and total disc diameters derived from the ERT images were recorded in the same manner as the manual method. The accuracy of ERT measurements was evaluated by comparing them to manual measurements and expressed as a percentage.

To further validate the instrument's accuracy, a standing teak tree was selected, and ERT scans were conducted at three different heights from the ground. The tree was then felled, and cross-sections were taken at the exact heights where ERT readings were recorded. Manual measurements of the actual heartwood and total diameters were taken from these cross-sections, as shown in Figure 2, and compared to corresponding ERT-derived values.

For analytical consistency, diameter measurements were converted to area using the formula:

$$B=\pi r^2$$, where r is the radius in centimetres.

Subsequently, volume was calculated using the volume formula:

$$V=B\times H$$

where B is the basal area (cm²) and H is the height from the ground at which the ERT reading was taken (cm), assuming the log/tree cross-sections were approximately circular.

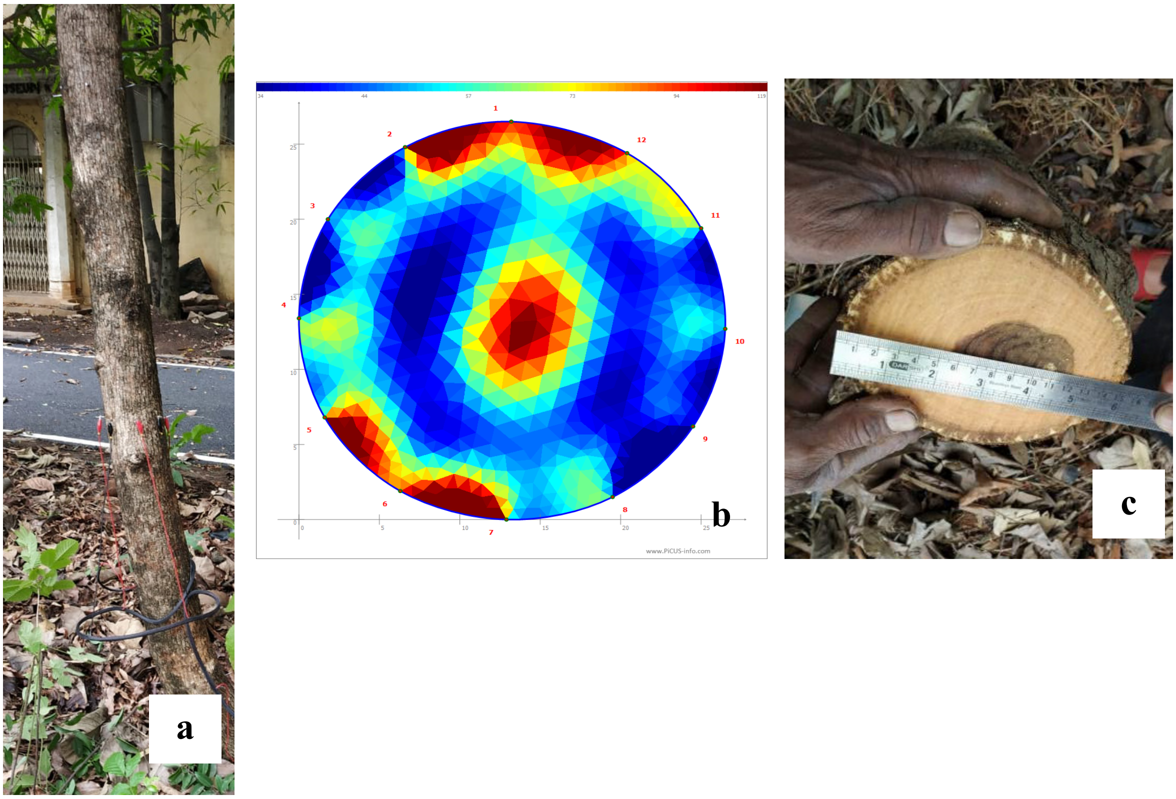


Figure 2. Representing a) ERT connected to the standing tree; b) Tomographic image of the standing teak tree; and c) Measuring the heartwood and sapwood after cutting

4. Results

The results derived from ERT analysis of the teak discs are presented in Table 1. The circumference of the selected discs ranged from 36 cm to 152 cm. The accuracy of heartwood area estimation using ERT, when compared to manual measurements, ranged from 77.76 % to 99.41 %, with 29 out of 33 samples demonstrating an accuracy of ≥80 %. Notably, 21 discs exhibited an accuracy greater than 90 %, with Disc 27 showing the highest agreement at 99.41 %.

Table 1. Representing the accuracy between actual and ERT readings of the teak disc

Disk No	Girth (cm)	Actual diameter in cm		ERT diameter in cm		Accuracy of Heartwood diameter (%)
		SW+HW	HW	SW+HW	HW	
1	90.0	28.75	22.30	28.40	19.25	86.32
2	75.0	23.35	21.05	23.09	16.70	79.33
3	104.0	30.15	25.15	28.90	22.85	90.85
4	89.0	25.70	20.30	25.40	20.15	99.26
5	87.0	26.05	23.75	25.50	21.30	89.68
6	90.0	25.20	20.50	24.80	20.00	97.56
7	87.0	26.85	15.35	25.50	14.90	97.07
8	104.0	32.20	24.85	31.90	24.35	97.99
9	120.0	34.50	27.55	32.10	26.10	94.74
10	110.0	34.85	22.10	34.30	21.59	97.69

Table 1 Continued

Disk No	Girth (cm)	Actual diameter in cm		ERT diameter in cm		Accuracy of Heartwood diameter (%)
		SW+HW	HW	SW+HW	HW	
11	135.0	43.00	34.40	41.10	32.45	94.33
12	125.0	39.80	31.80	38.30	31.45	98.90
13	116.0	36.15	30.60	35.10	25.15	82.19
14	107.0	34.07	31.00	33.70	30.00	96.77
15	123.0	41.00	33.35	39.60	32.70	98.05
16	85.0	25.25	21.10	23.89	18.57	88.01
17	36.0	11.05	6.75	10.50	6.15	91.11
18	140.0	44.60	39.40	44.00	35.85	90.99
19	93.0	25.75	20.50	23.60	19.30	94.15
20	120.0	33.55	25.45	32.10	23.60	92.73
21	100.0	31.55	20.95	30.51	20.50	97.85
22	92.0	28.40	24.10	27.00	19.00	78.84
23	100.0	32.00	20.35	31.10	19.85	97.54
24	116.0	30.55	24.65	29.30	24.20	98.17
25	144.0	46.00	38.00	45.10	37.30	98.16
26	152.0	48.41	43.15	48.10	42.05	97.45
27	136.0	42.15	33.75	41.30	33.55	99.41
28	135.0	39.75	32.20	38.60	28.80	89.44
29	100.0	30.65	25.85	30.20	20.10	77.76
30	110.0	31.25	29.65	30.30	23.45	79.09
31	120.0	36.95	31.75	35.10	25.55	80.47
32	77.0	22.85	18.00	21.40	14.75	81.94
33	120.0	36.70	29.30	35.30	25.85	88.23
Average		**32.70**	**26.33**	**31.67**	**24.16**	**91.58**
Minimum	**36**	**11.05**	**6.75**	**10.50**	**6.15**	**77.76**
Maximum	**152**	**48.41**	**43.15**	**48.10**	**42.05**	**99.41**
SD	**23.76**	**7.87**	**7.43**	**7.81**	**7.37**	**7.14**

The descriptive statistics, viz., minimum, maximum, mean, standard deviation (SD), coefficient of variation (CV), and standard error of mean (SEM) of actual and ERT heartwood (cm) in teak trees are given in Table 2. There were 33 teak trees for which the actual and ERT heartwood were determined. The actual heartwood ranged from 6.75 cm to 43.15 cm with a mean of 26.33 cm (Coefficient of variation of 28.2%) among 33 trees. The ERT heartwood ranged from 6.15 to 42.05 cm with a mean of 24.16 cm (CV of 30.5%). The mean actual heartwood was higher than the mean ERT heartwood of different trees, while the CV (%) of actual heartwood was lower than the CV (%) of the ERT heartwood over 33 teak trees.

Table 2. Descriptive statistics of actual and ERT heartwood in teak trees

Statistic	Actual heartwood (cm)	ERT heartwood (cm)
No. of tree disc	33	33
Minimum	6.75	6.15
Maximum	43.15	42.05
Mean	26.33	24.16
Standard deviation	7.43	7.37
Coefficient of Variation (%)	28.2	30.5
Standard error of mean	1.29	1.28

The two parameters of observed and ERT heartwood of 33 teak tree discs were found to have a significant positive correlation of 0.966. The rate of change in the ERT heartwood for a unit change in the actual heartwood of 33 teak trees is described in Figure 3. The ERT heartwood changed with a significant rate of change of 0.9582 cm for a unit change in the observed heartwood of trees. The regression model gave a significant coefficient of determination (R^2) of 0.9333 for predicting the changes in the ERT heartwood through observed heartwood of the teak trees.

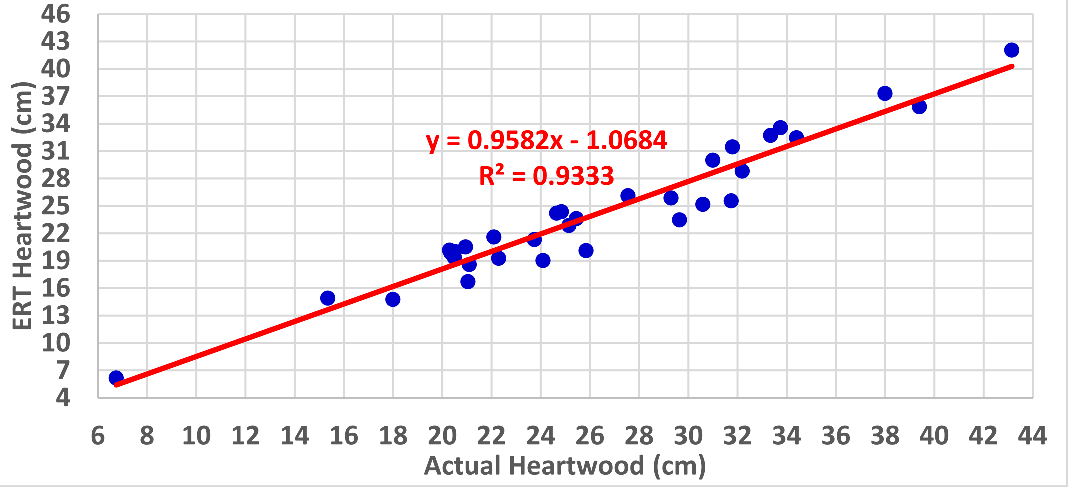


Figure 3. Relationship between observed and ERT heartwood diameter in teak disc.

The differences between the mean actual heartwood of 26.33 cm (Standard deviation of 7.43 cm) and ERT heartwood of 24.16 cm (Standard deviation of 7.37 cm) of the 33 teak trees were tested based on the student's t-test at 5% and 1% level of significance and are given in Table 3. The t-test indicated that there was no significant difference between the actual and ERT heartwood of the 33 teak trees.

Table 3. Testing the differences between actual and ERT heartwood in teak trees

Parameter	N	Mean	SD	t-calculated	t-critical (5%)	t-critical (1%)	Significance
Actual Heartwood	33	26.33	7.43	1.191	2.120	2.921	NS
ERT Heartwood	33	24.16	7.37				

Note. NS: Not significant; SD: Standard deviation; N: Number of trees

Based on the mean and standard deviation (SD) of the actual and ERT heartwood of teak trees, a grouping of 33 trees into 5 different groups viz., trees lying in the limits (i) less than (Mean – 2SD); (ii) (Mean – 2SD) to (Mean – SD); (iii) (Mean – SD) to (Mean + SD); (iv) (Mean + SD) to (Mean + 2SD); and (v) more than (Mean + 2SD) was made and the groups are described in Table 4. The limits of actual heartwood were (i) less than 11.5 cm; (ii) 11.5 to 18.9 cm; (iii) 18.9 to 33.8 cm; (iv) 33.8 to 41.2 cm; (v) more than 41.2 cm for the 5 groups respectively. Based on the actual heartwood, maximum number of 26 trees (78.8%) occurred under the 3rd group of (Mean – SD) to (Mean + SD), followed by 3 trees (9.1%) under the 4th group of (Mean + SD) to (Mean + 2SD). Two trees (6.1%) occurred in the 2nd group of (Mean – 2SD) to (Mean – SD); while one tree (3.0%) each occurred in the 1st group of less than (Mean – 2 SD) and the 5th group of more than (Mean + 2SD).

The limits of ERT heartwood of teak trees of the 5 groups were (i) less than 9.4 cm; (ii) 9.4 to 16.8 cm; (iii) 16.8 to 31.5 cm; (iv) 31.5 to 38.9 cm; (v) more than 38.9 cm, respectively. Based on the ERT heartwood, maximum number of 23 teak trees (69.7%) occurred under the 3rd group of (Mean – SD) to (Mean + SD); followed by 5 trees (15.2%) under the 4th group of (Mean + SD) to (Mean + 2SD); 3 trees (9.1%) under the 2nd group of (Mean – 2SD) to (Mean – 2SD); and one tree (3.0%) each under the 1st group of less than (Mean – 2SD) and 5th group of more than (Mean + 2SD).

Table 4. Grouping of teak trees based on the mean and standard deviation of actual and ERT heartwood

Parameter	Actual Heart-wood (cm)	No. of trees	% of trees	ERT Heart-wood (cm)	No. of trees	% of trees
<(Mean-2SD)	< 11.5	1	3.0	< 9.4	1	3.0
(Mean-2SD) to (Mean-SD)	11.5 to 18.9	2	6.1	9.4 to 16.8	3	9.1
(Mean-SD) to (Mean+SD)	18.9 to 33.8	26	78.8	16.8 to 31.5	23	69.7
(Mean+SD) to (Mean+2SD)	33.8 to 41.2	3	9.1	31.5 to 38.9	5	15.2
>(Mean+2SD)	> 41.2	1	3.0	> 38.9	1	3.0
Total		*33*	*100*		*33*	*100*

A linear relationship was expressed between manually measured and ERT-derived heartwood values, showing a strong correlation coefficient ($r = 0.93$), indicating a high degree of accuracy and consistency in the ERT method (Figure 3). Figure 4 illustrates selected examples of tomographic images captured from teak discs, highlighting the differentiation between sapwood and heartwood regions.

The results from the standing teak tree analysis are summarized in Table 5. ERT measurements were recorded at three heights from the ground: 30 cm, 107 cm, and 177 cm. The actual heartwood area and volume, measured post-felling, were found to be 22.41 cm^2 and 784.21 cm^3, respectively. Corresponding ERT-derived measurements yielded a heartwood area of 19.14 cm^2 and a volume of 669.86 cm^3. The accuracy of the ERT-based heartwood volume estimation was calculated at 85.42 %, confirming the method's reliability in standing tree assessments.

Table 5. Representing the actual and ERT readings of the standing teak tree

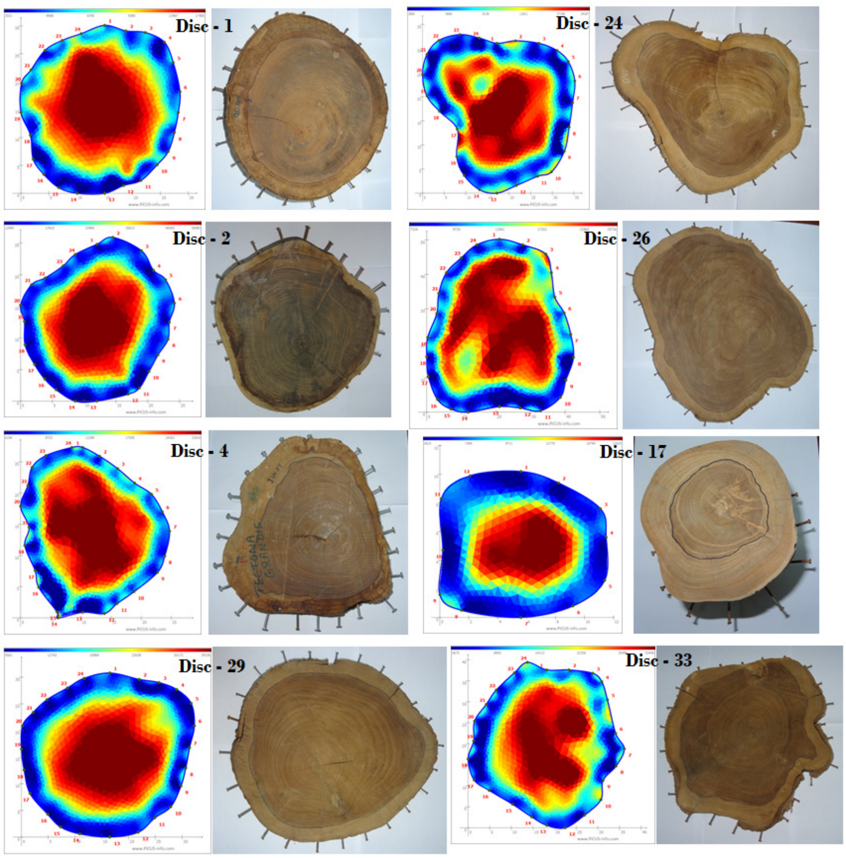
	Actual Readings			ERT Readings		
	First cut	Second cut	Third cut	First cut	Second cut	Third cut
Total (Sapwood+Heartwood+Bark)						
Average Diameter	12.55	13.55	15.95	12.15	13.20	15.35
Average Radius	6.28	6.78	7.98	6.08	6.60	7.68
Heartwood						
Average Diameter	3.25	4.25	7.55	3.00	3.80	7.05
Average Radius	1.63	2.13	3.78	1.50	1.90	3.53
Area		22.41			19.14	
Volume (cm^3)		784.21			669.86	
HW %		14.38			13.12	
SW %		85.62			86.88	
			85.42% similarity in heartwood volume			

5. Discussion

There is limited literature available on the use of Electric Resistance Tomograph (ERT) for tree assessment, and most existing studies have focused on softwood species. ERT has primarily been employed to evaluate wood decay and delineate the sapwood–heartwood boundary in coniferous and dicotyledonous trees, as reported by Nicolotti et al. [8], Brazee et al. [5], Lin et al. [9], Guyot et al. [10], and Elliott et al. [11]. However, such investigations have rarely been extended to tropical hardwood species, particularly commercially significant trees like teak (*Tectona grandis*).

In the present study, results from teak discs revealed that the heartwood consistently exhibited lower moisture content than the sapwood. This observation contrasts with findings by Chen et al. [12], who reported higher moisture content in the heartwood of softwood species. This discrepancy underscores species-specific variations in wood physiology, necessitating tailored ERT calibration. Generally, in tropical hardwoods, the heartwood tends to have considerably lower (often negligible) moisture content compared to sapwood.

This is attributed to the presence of dead cells in the inner wood region and the compressive effect exerted by the living cells in the outer sapwood, which leads to denser heartwood [13]. As a result, the highest electrical resistivity values were recorded in the heartwood regions of the teak discs, as illustrated in Figures 2 and 4.



Brown	Indicates higher resistance because of low moisture content, drier and denser wood
Red	Indicates high resistance because of 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

Figure 4. Representing the tomographic images along with respective teak discs.

The clear differentiation between sapwood and heartwood in ERT images is primarily based on colour contrast, which reflects the underlying physical and chemical properties of the wood. In teak, the heartwood is chemically enriched with phenolic compounds such as quinones and ketones, which contribute to its darker coloration compared to the sapwood [14]. This chemical distinction enhances the visual contrast between the two zones, facilitating accurate boundary identification. These differences are characteristic features of teak wood and contribute significantly to its commercial value.

Additionally, it is worth noting that the stems of softwood (temperate) trees typically exhibit a near-circular cross-sectional shape, whereas tropical hardwood species, including teak, often display more irregular stem forms. This morphological variability presents additional challenges in applying diagnostic tools like ERT, underscoring the importance of species-specific calibration and interpretation.

5. Conclusion

The present study demonstrated the effectiveness of Electric Resistance Tomography (ERT) in assessing hardwood tree species such as *Tectona grandis* (teak). The observed resistivity pattern—characterized by higher resistivity in the inner regions (heartwood) and lower resistivity in the outer regions (sapwood) reflects the natural variation in moisture content and wood density across the cross-section. This distinct pattern underscores the utility of ERT in detecting the presence, absence, and extent of heartwood at the time of harvest, thereby aiding in the reduction of potential financial losses. Accurately quantifying heartwood content also enables more precise profit estimation for commercial-scale timber production. Furthermore, trees exhibiting superior heartwood formation can be targeted for genetic studies, facilitating the selection and propagation of elite genotypes. Such targeted breeding and plantation strategies can significantly enhance productivity and economic returns in teak cultivation.

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Competing interests

The authors declare that they have received no financial support for the preparation of this manuscript and have no competing interests to disclose.

Ethics approval and Consent to participate

The collection of leaf samples in this study was carried out in accordance with applicable local and national guidelines. All samples were obtained from cultivated plants, and no endangered or protected species were involved.

Data availability

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

Consent to Publish

All authors have read and approved the final manuscript and consent to its publication.

Clinical trial number

Not Applicable

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