

Health status assessment of tropical trees in Malay beechwood (*Gmelina arborea* Roxb.) plantation using electrical resistivity method and electrical impedance tomography

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Abstract

This study investigates the tree health status of a Malay beechwood (*Gmelina arborea* Roxb.) plantation using the non-destructive four-point electrical resistivity method and electrical impedance tomography (EIT). Twenty standing *G. arborea* trees (T1-T20) of different stem diameters were selected for evaluation. The electrical resistivities of the sampled trees were measured with varying current penetration and subjected to descriptive statistical analysis, analysis of variance (ANOVA), and correlation analysis. EIT tomograms were generated for three trees to corroborate the electrical resistivity findings. Subsequently, the trees were felled to inspect internal decay visually. Healthy trees exhibited a consistent pattern of increasing electrical resistivity from sapwood to heartwood, ranging between 58 Ωm and 1797 Ωm , while unhealthy trees, T1 and T6 were characterized by irregular electrical resistivity patterns with exorbitant mean values of 193,508 Ωm and 5,542 Ωm , respectively. Also, we found a negative significant correlation between stem diameters and electrical resistivity at the core stem. The ANOVA and follow-up test showed significant variability in the mean electrical resistivity of healthy trees. Trees T3 and T8, which exhibited lower mean electrical resistivity values of 157 Ωm and 183 Ωm , respectively, were determined to be healthier. The EIT tomograms and cross-sectional analyses of the felled trees corroborated the results obtained from the four-point electrical resistivity method.

Introduction

The quality of trees in forest plantations is critical to ensuring the production of high-quality wood products. Internal defects such as decay, cavities, and cracks significantly affect forest health and timber quality (De Petris et al., 2020; Papandrea et al., 2022). These defects not only reduce wood density but also diminish both the ecological and economic value of trees (Beall & Wilcox, 1987; Goncz et al., 2018). In urban environments, such internal defects compromise the structural stability of trees, posing safety risks (Papandrea et al., 2022; Santini et al., 2019). As forestry industries face increasing economic pressure to maximize value, evaluating tree vigor and forest stand health has become an essential aspect of sustainable forest management (Wang et al., 2007).

Non-destructive testing (NDT) techniques offer a valuable approach for investigating internal tree defects without altering material properties (Dwivedi et al., 2018). These techniques enable early detection of issues such as wood decay, cavities, and cracks, even when external indicators are absent (Wang et al., 2004). NDT methods like stress wave analysis, acoustic tomography, and electrical resistivity have proven effective in ensuring wood quality and maintaining the structural integrity of trees in both urban and plantation settings. For example, Wei et al., (2022) used stress wave analysis to detect internal decay in *Populus euphratica* in China's arid regions, achieving over 80% accuracy. Their study revealed correlations between decay, tree morphology, and water conditions, demonstrating the utility of this technique in diagnosing internal defects.

Acoustic tomography has also been widely studied for its effectiveness. Muşat, (2023); Muşat et al., (2020) investigated fire-damaged spruce and lime trees, demonstrating how sound wave propagation

and resistograph measurements complement each other in diagnosing internal defects. Similarly, Proto et al., (2020) showed that sonic tomography could accurately predict ring shake in chestnut trees, distinguishing between healthy and defective trees without compromising their biological activity. These examples underscore the role of NDT in identifying defects that traditional methods often miss.

Electrical resistivity and electrical impedance tomography (EIT) are other advanced NDT techniques used to diagnose internal tree defects. These methods rely on measuring changes in electrical resistance caused by decay, as fungal activities increase ion concentrations in decayed wood. EIT, in particular, complements resistivity methods by generating detailed tomograms that reveal the internal structure of trees. The suitability of EIT to better detect brown and white rot fungi gave it a comparative advantage over acoustic methods (Olaoye & Ojo, 2022). Furthermore, studies have validated the effectiveness of these techniques in detecting early-stage decay in tropical species (Anderson, 1997; Gao et al., 2019; Larsson et al., 2004; Martin, 2009) such as with *Terminalia catappa* and *Senna alata* (Soge et al., 2018, 2019).

The transformative potential of NDT methods to monitor tree health, detect defects, and support sustainable practices underscores the need for broader research, investment, and adoption, particularly in tropical forestry sectors in countries like Nigeria. These methods not only ensure the safety and productivity of urban and plantation trees but also maximize wood quality for industrial applications.

However, in Nigeria, the adoption of NDT has been limited partly due to the lack of advanced equipment. Notwithstanding, studies have highlighted its potential for tropical forestry applications. Olaoye et al., (2021); Olaoye, (2019); Olaoye & Ojo, (2022); Olaoye & Okon-Akan, (2020) demonstrated the use of acoustic techniques for assessing wood quality in tropical trees, thus, emphasizing the relevance of NDT in commonly used Nigerian wood species. Also, A clinical test of the electrical resistivity method was performed on selected Nigerian wood species (Soge et al., 2018, 2019). However, these studies overlooked deeper current depths, did not utilize EIT for validation, and failed to consider its implementation in forest plantations.

Notably, our preliminary surveys involving visual inspection of the *Gmelina arborea* plantation revealed significant wood decay, evidenced by dried wood, fallen leaves, and several fallen trees, suggesting that the prolonged activities of brown-rot fungi (*Poria cocos*) caused these trees to collapse. This poses a serious threat to the sustainability of the plantation

Building on these efforts, we applied a hybrid approach of using the four-point electrical resistivity method and EIT in this study to assess the internal decay and salvage of the plantation, hence, providing critical insights for forest management. By integrating these resistivity methods to forestry practices, forest managers can mitigate risks, improve plantation sustainability, and enhance the long-term viability of forest ecosystems.

Materials and Method

Sampling Technique and Method

We selected twenty *Gmelina arborea* standing trees from the Federal College of Forestry plantation, Ibadan, Southwest Nigeria, for this study. The selection included presumed healthy trees, which showed no visible signs of defects, and unhealthy trees, identified by visible indicators such as cracks, damaged bark, or the absence of a crown. The trees were tagged T1 to T20.

Field Measurement

We measured the electrical resistivity of the sampled *Gmelina arborea* trees using the four-point electrical resistivity method, as described by Larsson et al., (2004). The vertical variation of resistivity with depth was assessed using the Schlumberger electrode configuration on a reduced scale, following the approach outlined by Reynolds et al., (2006).

For this measurement, we strategically positioned four electrodes along the length of the tree trunk: two current electrodes (C1 and C2) and two potential electrodes (P1 and P2). The current electrodes, separated by a distance AB, were used to introduce a direct current into the tree stem, while the potential electrodes, separated by a distance MN, were used to measure the potential difference between two points on the trunk (Figs. 1 and 2a).

To ensure sufficient depth of current penetration, we used potential electrode separations of 4 cm, 6 cm, 8 cm, and 10 cm. Concurrently, the current electrode positions were varied incrementally between 4 cm and 50 cm at 2 cm intervals. This systematic approach enabled the investigation of the vertical resistivity profile of the tree trunk, providing insights into its internal structure.

The separation of the current electrodes (AB) is generally proportional to the depth of current penetration (Herman, 2001). Therefore, an increase in electrode separation is expected to result in deeper current penetration. To minimize potential injuries to the tree stems and prevent short circuits, which are occasionally caused by conventional electrodes of 14 mm thickness, we used smaller electrodes with a thickness of 3.84 mm.

Following the experimental setup illustrated in Fig. 2a, we measured the electrical resistance values (R_a) of the *G.arborea* trees at various points using the Miller 400D digital resistance meter, commonly called an earth resistivity meter. Subsequently, the apparent resistivity values (ρ_a) were calculated using Eq. 1.

$$\rho_a = R_a K$$

where K is the geometric factor K of the electrode configuration calculated using Eq. 2,

$$K = 2\pi \left[\left(\frac{1}{AM} - \frac{1}{MB} \right) - \left(\frac{1}{AN} - \frac{1}{NB} \right) \right]^{-1}$$

AM, MB, AN, and NB are the electrode separations as shown in Fig. 1 (Reynolds 2011).

After screening the apparent resistivity values (ρ_a) obtained using the resistivity meter, we subjected 3 trees, one presumed healthy and two suspected of having internal defects – to further validation through the EIT experiment. To conduct the EIT measurements, we inserted point-like electrodes (galvanized nails) around the circumference of the tree stem at breast height, as shown in Fig. 2b. These electrodes were connected to the EIT device, which injected a maximum current of 20 mA into the tree stem to determine the spatial resistance distribution across the stem cross-section. The electrical resistivity data collected from the EIT device were processed using the PiCUS Q74 Treetric software application, which generated tomograms (resistivity images) representing the internal structure of the tree stem. The number of electrodes used for this experiment was based on the circumference of each tree. The diameter at breast height and at base was measured using the girthing tape.

Afterward, we fell all sampled trees to visually inspect the extent of internal decay and validate the resistivity methods.

Statistical analysis

We subjected the electrical resistivity values obtained from the 20 selected trees to descriptive statistics. We used the Pearson correlation to determine the relationship between the stem diameters and mean resistivity values of the *Gmelina arborea* trees. Additionally, we performed an analysis of variance (ANOVA) to assess the statistical differences among the mean resistivity values of the sampled trees, and the potential electrode separation.

Results

Electrical resistivity

Table 1 presents the minimum and maximum resistivity values, variance, range, and stem diameters for the examined trees. Tree T19 exhibited a minimum resistivity value of 59 Ω m, while tree T1 recorded a maximum resistivity value of 618,597 Ω m. Trees T1 and T6 exhibited exorbitantly higher resistivity range values of 602,361 Ω m and 75,797 Ω m, respectively, hence, we analyzed them separately. We suspected that the external defects in trees T1 and T6 (Fig. 3a and Fig. 3b) are evident for their irregular resistivity spikes (Fig. 5),

The resistivity profiles of current electrode half-separation for trees T2, T3, T4, T5, T7, T8, T9, T10, T11, T12, T13, T14, T15, T16, T17, T18, T19, and T20 were afterward displayed in Fig. 4. The resistivity plots revealed a consistent pattern across the trees, showing a gradual increase in resistivity values from the sapwood to the heartwood. All the trees recorded resistivity values below 200 Ω m at the current electrode half-separation $\left(\frac{AB}{2}\right)$ and MN of 4 cm, being the minimum depth of current penetration. Conversely, tree T18 had the highest resistivity of 1,797 Ω m at $\frac{AB}{2}$ and MN of 50 cm and 10 cm, respectively (maximum depth of current penetration).

Regarding stem diameters, trees T5 and T20 had the smallest diameter at breast height (25.14 cm) and at the base (31.35 cm), respectively while tree T15 had the largest diameter at breast height and base, measuring 71.93 cm and 81.51 cm, respectively.

Furthermore, the analysis of variance (ANOVA) (Table 2) conducted for the remaining 18 trees revealed a significant difference in the mean resistivity values and interaction with potential electrode separation, hence, the follow-up test assisted us in grading the sampled trees according to their health status (Fig. 6). Notably, Pearson correlation analysis showed a negative significant correlation between the resistivity and stem diameters of the sampled trees at the core stem (MN = 10cm), with correlation coefficients of -0.563 and -0.551 for diameter at breast height and diameter at the base, respectively (Table 3)

Electrical impedance tomography (EIT)

Following the post hoc analysis of the resistivity profiles of the sampled trees, we purposefully subjected trees T3, T4, and T14, representing both presumed healthy and unhealthy trees to EIT validation. Our findings of the EIT tomograms along with the corresponding cross-sections of the trees after felling were presented in Fig. 7 to 9. Tree T3, identified as one of the healthiest samples, exhibited an EIT tomogram that shows a gradual increase in electrical resistance from the sapwood toward the heartwood or (core wood) (Fig. 7a). In the tomogram, the blue regions indicate low electrical resistance values corresponding to the sapwood, while the red regions signify high resistance values associated with the heartwood. The cross-sectional photograph of tree T3 confirmed the absence of visible internal decay or hollows (Fig. 7b).

In contrast, the EIT tomogram of tree T4 (Fig. 8a) reveals significant decay within the heartwood, indicated by the dominance of blue colouration, with the internal decay process gradually extending into the sapwood. The tomogram of tree T14, evidenced by the red color in its stem core (Fig. 9a), shows similarities with T3 (Fig. 7a), particularly in the high electrical resistance values observed at its heartwood. However, the cross-section of the tree (Fig. 9b) confirms the presence of a hollow.

Table 1
Resistivity values (Apparent) and tree diameters of the *Gmelina arborea* trees

Trees	Min. (Ωm)	Max. (Ωm)	Mean (Ωm)	Variance (Ωm)	Range (Ωm)	S.E (Ωm)	Dbh (cm)	Db (cm)
T1	16,236	618,597	193,509	3.42x10 ¹⁰	602,361	37,763	28.01	32.78
T2	74	674	312	31,517	599	36	34.37	43.92
T3	79	299	157	4,668	219	14	50.60	57.29
T4	141	731	541	28,549	590	34	46.47	55.06
T5	102	1,556	660	195,828	1,454	90	25.14	33.10
T6	576	76,372	5,542	2.43x10 ⁸	75,797	3,184	34.05	38.83
T7	58	605	318	26,741	547	33	45.51	56.97
T8	66	271	183	2,600	205	10	49.01	60.15
T9	81	535	290	17,839	454	27	47.10	58.24
T10	82	490	293	13,306	408	24	53.79	80.20
T11	60	664	348	29,705	604	35	41.69	54.42
T12	108	1,120	589	90,020	1,012	61	44.24	51.88
T13	92	538	285	14,029	445	24	34.69	43.60
T14	95	1,525	670	183,159	1,430	87	29.92	40.74
T15	62	503	295	15,914	440	26	71.93	81.51
T16	72	988	430	76,516	916	56	32.15	44.88
T17	60	502	297	14,190	442	24	47.74	60.31
T18	145	1,797	860	229,612	1,652	98	31.35	38.35
T19	59	567	301	22,339	508	31	50.60	59.74
T20	88	536	252	17,200	448	27	25.88	31.35

Min. – Minimum

Max. – Maximum

S.E. – Standard Error

Dbh – Diameter at breast height

Db – Diameter at the base

Table 2
ANOVA showing the interaction between the resistivity and potential electrode separations (MN) of *Gmelina arborea* trees

Source	df	Mean Square	Sig.
Tree	17	876705	0.001
MN	3	5063872	0.001
Tree * MN	51	123055.7	0.001
Error	360	5134.306	
Total	431		
* Significant at $\alpha_{0.05}$			

Table 3
Pearson Correlation between the mean resistivity values and the stem diameters of the sampled trees

$\sqrt{\text{varvec}\rho_{\text{varvec}a}}$	Dbh	Db
Mean	-0.476*	-0.473*
MN (4cm)	-0.267ns	-0.286ns
MN (6cm)	-0.288ns	-0.302ns
MN (8cm)	-0.450ns	-0.447ns
MN (10cm)	-0.563*	-0.551*
* Significant at $\alpha_{0.05}$		

Discussion

Table 1 and Fig. 5 highlight that Trees T1 and T6 exhibit exorbitantly high and irregular resistivity patterns, with Fig. 3 confirming their unhealthy status due to visible external decay. Our findings agreed with those of Bieker & Rust, (2010) who evaluated the resistivity of sapwood and heartwood width in Scots pine (*Pinus sylvestris* L.) trees and found a steep pattern of low and high resistivity values. Similarly, Soge et al., (2018, 2019), detected unhealthy trees through abrupt changes in resistivity, corresponding to decay and hollowing.

Additionally, the gradual increase in resistivity from sapwood to heartwood observed in this study supports Fazriati et al., (2022), who documented similar trends in healthy *Swietenia mahagoni* and *G.*

arborea. Similarly, Manyazawale & Ostrofsky, (1992) reported lower internal electrical resistance (IER) in sapwood compared to heartwood, with Guyot et al., (2013) noting lower resistivity in outer wood and higher resistivity in the inner wood of conifers. (Fazriati et al., 2022) attributed this trend to the higher moisture content in the sapwood of these trees.

Notably, Smith & Shortle, (1988) posited that reduced electrical resistivity at the core wood indicates early decay, while cavities elevate resistivity due to their non-conductive nature (Larsson et al., 2004). In the same vein, Soge et al., (2019) claimed that hollows in trees can result in a large increase in the electrical resistivity values.

These pieces of literature infer that healthy trees are identified by a consistent pattern of gradual increase in electrical resistivity from outer to core wood. Conversely, unhealthy trees have inconsistent variation in electrical resistivity from outer to core wood. Notably, in the core wood of unhealthy trees, low resistivity is associated with internal decay while steep high resistivity identifies with hollow.

The results we obtained for the apparent resistivity suggest that except for T1 and T6, all trees are likely healthy. However, the significant differences in mean resistivity and its interaction with potential electrode separation, revealed by ANOVA, indicate variability in the trees' health. This was confirmed by the post-hoc analysis, hence, grading of the trees' healthiness as shown in Fig. 6. For validation, three trees—presumed healthy (T3), fairly unhealthy (T4), and unhealthy (T14)—were assessed using Electrical Impedance Tomography (EIT).

The tomograph in Fig. 7a showing a colour gradient from blue to red towards the core, indicates a gradual resistivity increase from outer wood to core wood depicting tree T3 as healthy, as confirmed by the cross-section in Fig. 7b. Hence, we confirm that the EIT validates our classification of tree T3 as healthy. In the same vein, we sort validation of tree T4 as unhealthy and found that the blue colouration is an indication of low resistivity due to decay from fungal activity (Fig. 8a), as noted by Brazee et al., (2011); Soge et al., (2021). This explains the slight decline in its resistivity curve at $\frac{AB}{2} = 26\text{cm}$ (Fig. 4a). The decay is further evidenced by the cross-section in Fig. 8b, confirming T4 as fairly unhealthy.

Tree T14, despite being hollow, demonstrates higher electrical resistivity at the heartwood (indicated by red colouration), like the healthy tree T3. Smith & Shortle, (1988) linked high core resistivity to the presence of hollows or cavities, because hollows are non-conductive (Larsson et al., 2004). Nevertheless, we observed that T14 exhibits a more intense red colouration in a specific region compared to T3, signifying a higher mean resistivity. Thus, the elevated mean resistivity and pronounced red colouration in the EIT facilitate the identification of hollow trees.

Finally, the negative correlation between stem diameter and mean resistivity indicates that *G. arborea* trees with wider stems exhibit lower resistivity, particularly in the core. This suggests that larger diameters may signal a higher risk of internal decay. These findings align with Wei et al., (2022), who reported a positive correlation between internal defects and stem diameter, which could be due to increased moisture or ion concentration from fungal activity (Soge et al., 2021).

Conclusion

In this study, we evaluated the health status of selected *Gmelina arborea* trees using the non-destructive electrical resistivity method and electrical impedance tomography (EIT). Our results indicated that healthy trees exhibit a consistent pattern of increasing electrical resistivity from the outer stem toward the core, whereas unhealthy trees show irregular variations in resistivity. The EIT validation confirmed that mean electrical resistivity is a reliable indicator for assessing tree health. Additionally, we found that *G. arborea* trees with larger stem diameters tend to have lower electrical resistivity, suggesting a higher susceptibility to internal decay.

These findings underscore the effectiveness of electrical resistivity and EIT as non-destructive tools for detecting internal defects and comprehensively assessing tree health. Consequently, we recommend the application of these methods for routine monitoring of *G. arborea* plantations to support sustainable tree management practices.

Declarations

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Disclosure statement

The authors report that there are no competing interests to declare.

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Figures

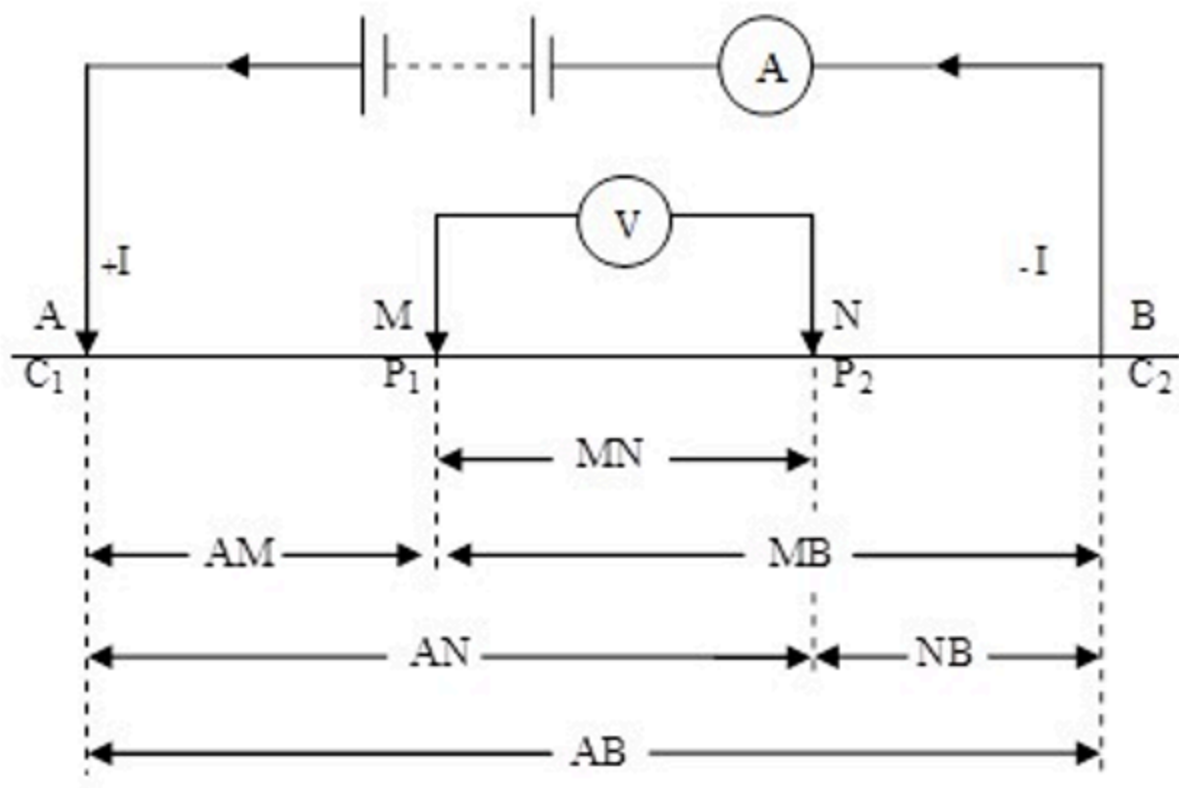


Figure 1

General electrode configuration for resistivity measurement. C_1 and C_2 represent the current electrodes while P_1 and P_2 are the potential electrodes. MN , AM , MB , AN , NB , and AB are the electrode separations. AB represents the current electrode separation while MN is the potential electrode separation.



(a)



(b)

Figure 2

Field set-up of the electrical resistivity methods: **(a)** Four electrodes (two current electrodes C1, C2, and two potential electrodes P1, and P2) are arranged along the length of the tree trunk and connected with metal clips to the earth resistivity meter; **(b)** Electrical impedance tomography measurement using PICUS TreeTronic 3 with the electrodes inserted at breast height around the entire circumference of the tree.



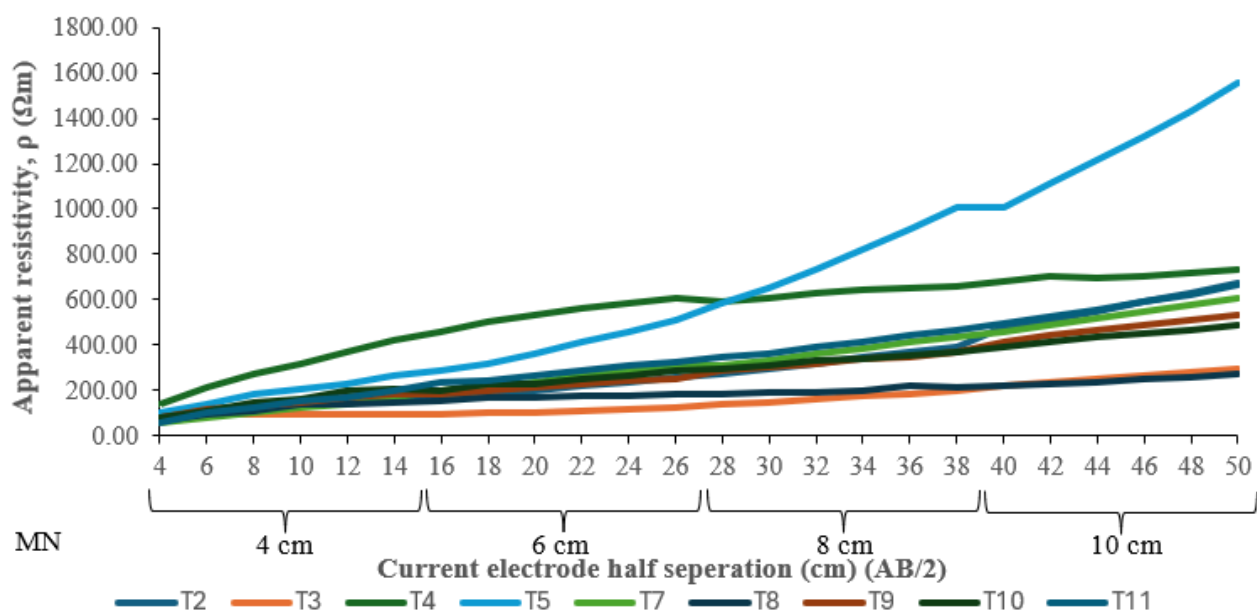
(a)



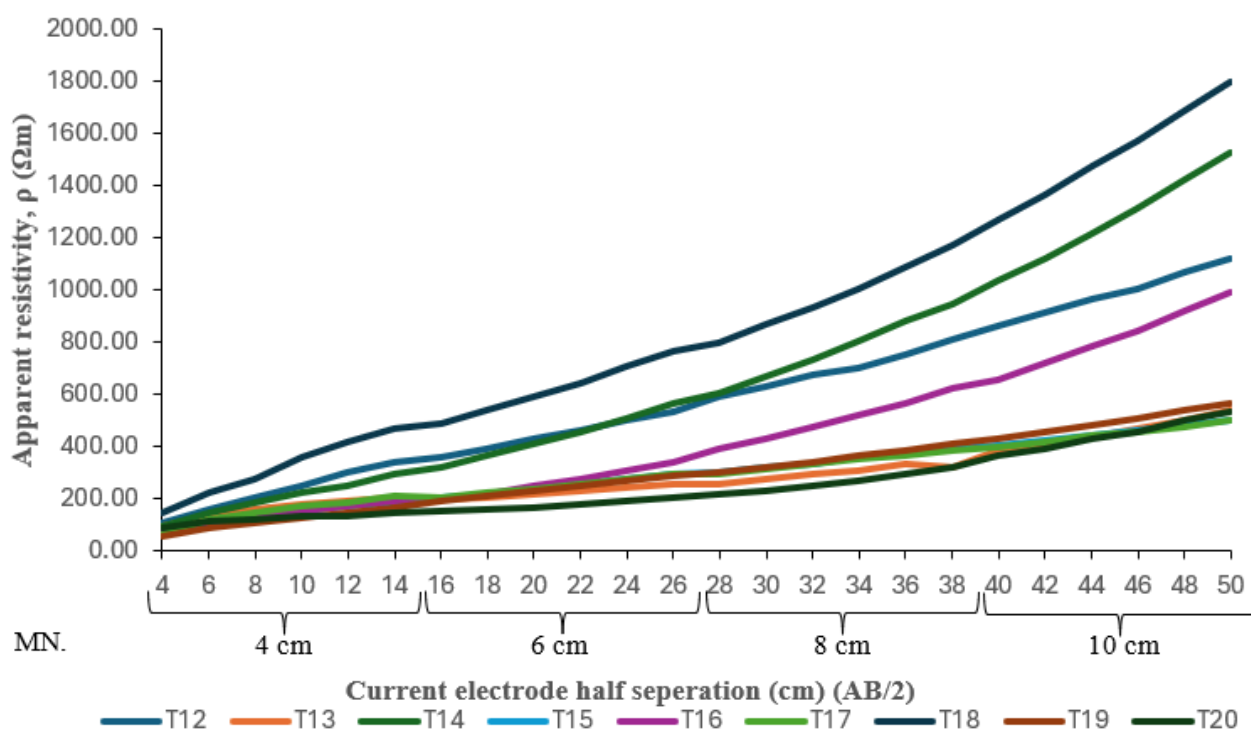
(b)

Figure 3

Unhealthy stands of *G. arborea* trees: (a) T1 and (b) T6, with visual evidence of external defects: cracks, damaged bark, and no crown.



(a)



(b)

Figure 4

Electrical resistivity plots of *Gmelina arborea* trees: (a) Trees T2, T3, T4, T5, T7, T8, T9, T10 and T11; (b) trees T12, T13, T14, T15, T16, T17, T18, T19 and T20.

MN – Potential Electrode separations = 4cm, 6cm, 8cm and 10cm

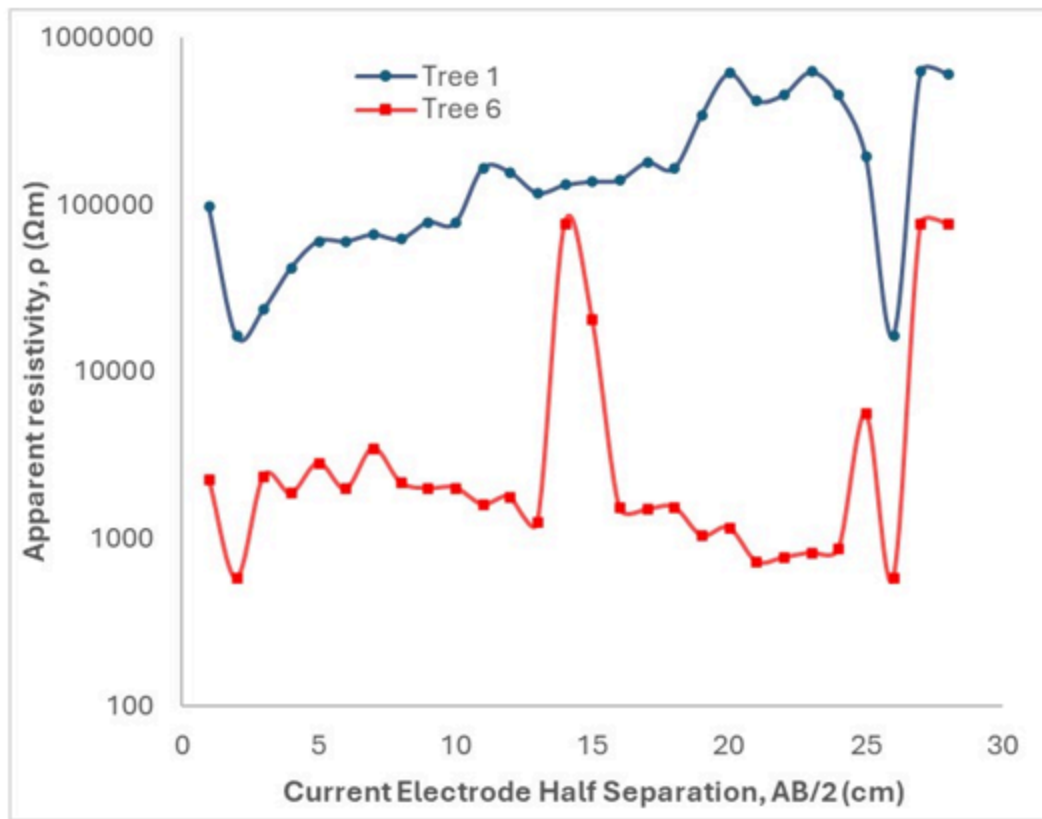


Figure 5

Electrical resistivity plots of *Gmelina arborea* trees T1 and T6

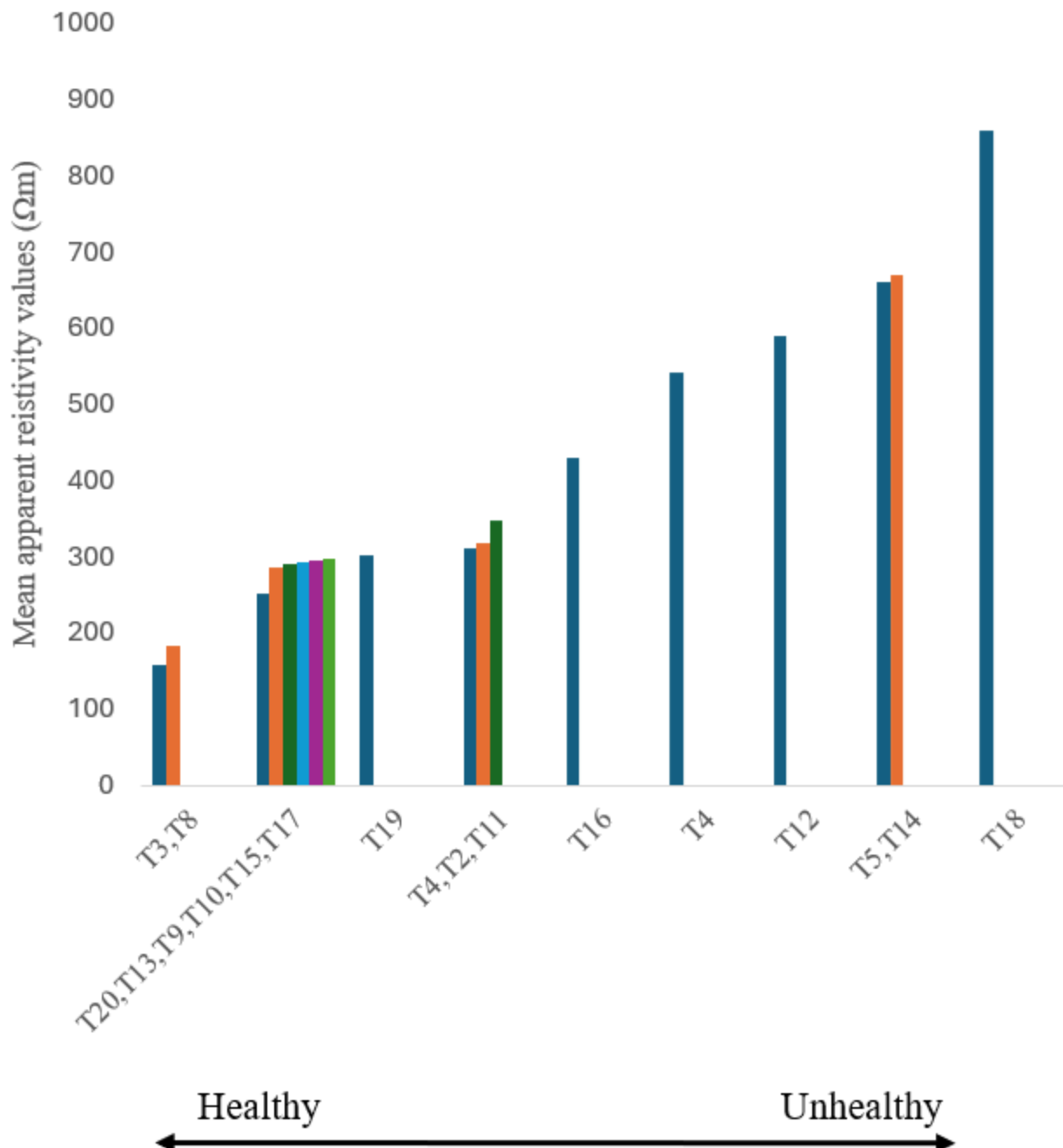
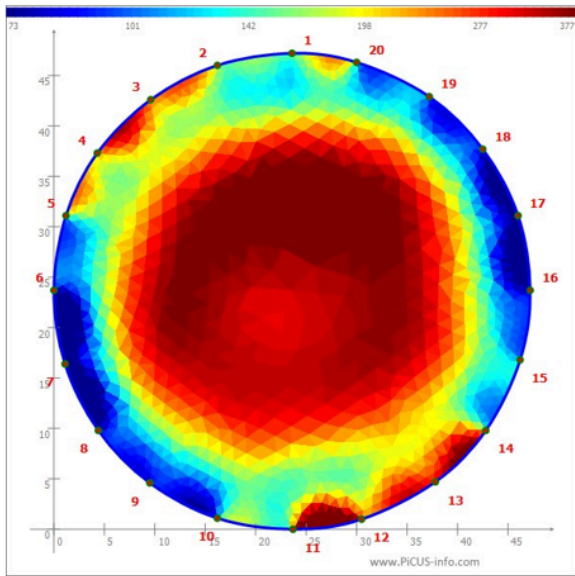


Figure 6

Health grading of the 18 *Gmelina arborea* trees showing nine subsets significant at $\alpha_{0.05}$



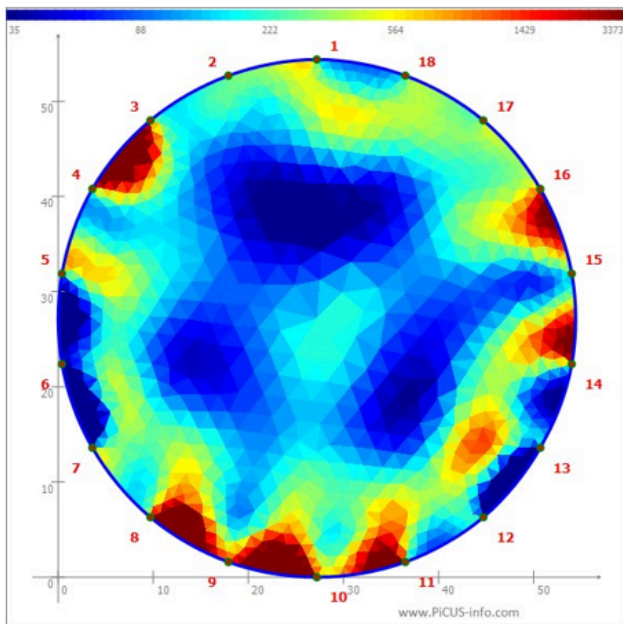
(a)



(b)

Figure 7

Healthy *Gmelina arborea* tree (T3): (a) Electrical Impedance Tomogram: The blue colour represents low values of electrical resistance (sapwood) while the red colour represents high values of electrical resistance (heartwood); (b) A cross-section of the stem after cutting shows no visual



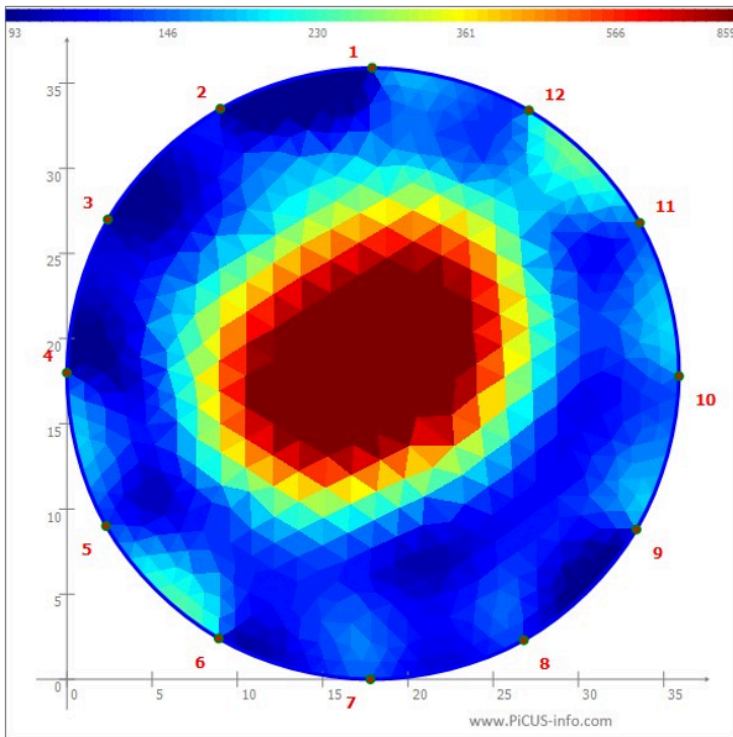
(a)



(b)

Figure 8

Decayed *Gmelina arborea* tree (T4): (a) Electrical Impedance Tomogram: The blue colour represents low values of electrical resistance (decayed heartwood) while the yellow and red colours represent high values of electrical resistance (healthy region of the sapwood). (b) A cross-section of the decayed tree trunk after felling.



(a)



(b)

Figure 9

Hollowed *Gmelina arborea* tree (T14): (a) The blue colour represents low values of electrical resistance (sapwood) while the red colour represents comparatively high values of electrical resistance (hollow heartwood); (b) A cross-section of the stem after cutting showing visual evidence of hollow at the core stem.